The Effect of CrossFit vs. Resistance Training on Aerobic, Anaerobic, and Musculoskeletal Fitness

by

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Abstract

Background: Although a number of studies to date have investigated the acute physiological outcomes of single CrossFit Workout Of the Days (WODs) and/or fitness attributes of well-trained CrossFit athletes, the variable populations, training histories, and short duration analysis of participants in these studies makes it difficult to evaluate the effectiveness of long term (multi-week) CrossFit training to improving fitness attributes (especially when compared to more traditional resistance training modalities). Thus, the primary purpose of the current study was to investigate the effects of multi-week CrossFit training on specific fitness attributes compared to a traditional resistance training intervention (of equivalent duration). **Participants, Measures, and Training**: 30 recreationally active male and female adults (BM: 70.0 ± 9.9kg, age: 23.2 ± 3.23 years) were randomly assigned to one of 3 groups (FE, CF, TRAD; n=10). All participants performed the same battery designed to assess musculoskeletal strength, endurance, and power, as well as aerobic and anaerobic power, and anaerobic metabolism outcomes. Following pre-testing, the intervention groups performed 6 weeks of resistance training; participants in the CrossFit (CF) group performed up to 4 days/week of researcher supervised CrossFit modality training, while those in the traditional resistance training group (TRAD) performed a more conventional form of resistance training (at the same frequency, while also supervised by a member of the research team). The free exercise group (FE) was asked to maintain their pre-study exercise regimens for the entire study duration, and was not supervised by a member of the research team during any training session. Following 6 weeks of training, the same test battery (completed prior to training) was performed; detailed records of all additional physical activity (including exercise performed external to study sanctioned workouts) were also analyzed to determine training time and subjective intensity. **Results:** The major findings from the primary analyses were: 1. post-training mean lower body power output (measured via 30 second Wingate cycle ergometer test) of CF was significantly lower than both FE ($p = .004$, CF < FE by 96.36 ± 30.98 watts) and TRAD ($p = .025$, CF < TRAD by 66.71 ± 28.09 watts); 2. post-training mean upper body endurance (measured via bent-arm hang time to failure) of CF was significantly greater than TRAD ($p = .026$, CF > TRAD by 4.63 ± 1.95 seconds). Secondary analyses revealed that CF incurred positive changes in all measures of strength ($p < .05$), as well as significant improvements in shuttle run test performance (0.85 ± 0.22 stages, $p = .004$), estimated $VO2_{max}$

(2.10 ± 0.78 ml/kg/min, $p = .025$), and general lower body endurance (measured via maximum bodyweight squats in 1 minute) (4.20 ± 1.42 repetitions, $p = .026$). There were, however, no differences in total time spent exercising ($p = .440$), as well as time spent performing moderate ($p = .489$) and vigorous ($p = .478$) intensity physical activity between groups (based on participant training log data recorded throughout the study duration). **Conclusion:** While CF elicited significant improvements in aerobic power, whole body muscular strength, upper body pull endurance, and lower body general endurance over time, this group also experienced a significant decrement in lower body anaerobic power from pre to post training. Compared to TRAD, CF only elicited greater improvements in upper body muscular endurance, and greater decrements in lower body anaerobic power. Thus, relative to traditional resistance training, CrossFit may be superior at improving upper body endurance, inferior at improving lower body anaerobic power, and similar at improving whole body strength, aerobic power, and lower body general endurance in recreationally active adults (after 6 weeks of training). Future research should examine if these adaptations can be extended to other populations (such as elite endurance athletes) who may benefit from concurrent improvements in both strength and aerobic fitness, or athletes involved in sports requiring substantial amounts of upper body muscle endurance (such as rock climbing). Future studies should also examine the molecular and genetic factors underpinning changes in fitness during concurrent training (which is used during CrossFit workouts).

Preface

This thesis is an original work by David Kelly Mcweeny. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name “The Effect of CrossFit vs. Resistance Training on Aerobic, Anaerobic, and Musculoskeletal Fitness”, No. Pro00072960, 5/24/2018.

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Cheers,
- D.M.

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Chapter 1: Purpose, Justification, and Hypothesis

Introduction

High intensity interval training (HIIT) has been used for many years as a training modality for improving fitness in a variety of athletic and non-athletic populations (Bergeron et al., 2011). However, researchers have more recently reported the growing presence of HIIT in training programs designed to improve aerobic power (Gillen & Gibala, 2014; R. B. O'Hara et al., 2012). The increase in this type of training is likely due to a growing body of literature supporting the use of HIIT over continuous endurance exercise due to its proposed ability to improve aerobic power (i.e., maximal oxygen uptake, also known as VO_{2max}), in less time per week than traditional exercise prescriptions (Garber et al., 2011; Gibala & McGee, 2008; Gibala & Jones, 2013; Hood, Little, Myslik, Gibala, & Tarnopolsky, 2011; Skelly et al., 2014) and low intensity aerobic training programs (Weston, Taylor, Batterham, & Hopkins, 2014).

Application of HIIT principles to resistance training is also becoming increasingly common amongst training enthusiasts who wish to improve both musculoskeletal and aerobic fitness (Bergeron et al., 2011). Often referred to in the literature as “High Intensity Power Training” (HIPT), this relatively new approach to weight training incorporates a variety of multiple-joint resistance exercises (i.e. squat, overhead press, deadlift) with the goal of performing all movements either as fast as possible, or with the highest number of possible repetitions/rounds (for exercises performed in a circuit style) in a predetermined amount of time (Smith, Sommer, Starkoff, & Devor, 2013).

CrossFit Training

One particularly popular variant of HIPT is CrossFit; CrossFit can be defined as a modality of resistance training that combines cardiovascular and musculoskeletal exercises in “workouts of the day” (WOD), which are often comprised of a combination of aerobic (e.g. running), power (e.g. Olympic lifts), and gymnastic/bodyweight (e.g. pullups) exercises performed rapidly with free weights or bodyweight. CrossFit WODs also place an emphasis on limited or no rest periods between exercises (or groups of exercises), and often organize movements into circuits (i.e. consecutive completion of ≥3 exercises, performed back-to-back, without any rest between), usually lasting 10-20 minutes in duration (Butcher, Neyedly, Horvey, & Benko, 2015; Smith et al., 2013). Depending on the fitness level of CrossFit participants, these workouts may be repeated, combined, or coupled with warm-up, cool down, and/or flexibility drills (Smith et al., 2013).

Each CrossFit WOD is designed to focus on 1-3 different “elements”: monostructural metabolic conditioning (M), Gymnastics (G), and Weightlifting (W) (Glassman, 2010). These elements differ in the exercises, intensities, reps, sets, and rest periods used, as well as the predominant energy system(s) stressed during exercise. The CrossFit Training Guide (CFTG) provides definitions and exercise examples for each of the three modalities; these have been replicated in Table 2.

Within each CrossFit workout, the use of compound/“functional” movements (e.g. squats, deadlifts) is emphasized, while excluding most isolation exercises (e.g. seated leg extensions/leg curls). Compound movements involve the simultaneous contraction of more than one muscle group while performing the exercise; consequently, the movement of multiple joints at the same time is typical during compound exercises. Conversely, isolation exercises typically only involve the contraction of one or two muscle groups, and, as a result, are comprised of movements about a single joint. CrossFit’s emphasis of functional movements and actie avoidance of isolation exercises is, according to the CFTG, the primary reason why CrossFit is “radically more effective at eliciting nearly any desired fitness result”, relative to more traditional resistance training programs that utilize isolation exercises (Glassman, 2010). The authors also assert that “the soundness and efficacy of functional movements are so profound that exercising without them is by comparison a colossal waste of time” (Glassman, 2010), further noting that isolation movements are, by comparison, “ineffectual” at improving an individual’s fitness (Glassman, 2010).

The CFTG also offers a programming methodology that involves alternating workouts based on the number of elements in each workout. In a 3-days-on, 1-day-off training schedule, the first day always focuses on working a single element (i.e. either a single, slow, long distance effort (if the focus is M), a single, high level skill (if the focus is G), or a single heavy lift (if the focus is W)); conversely, the second day is comprised of two-elements, performed at a moderate to vigorous intensity, in a couplet or super-set fashion for 3-5 rounds as fast as possible; finally, the third day involves performing 3 elements at a light to moderate intensity in a triplet or circuit fashion, with the intent of completing as many rounds of the circuit as possible in a 20 minute time limit (Glassman, 2010).

Although CrossFit involves a somewhat cyclical rotation of combined fitness "elements" (and subsequent training time is therefore split between a multitude of different intensities, for different durations, using different exercises), no further periodization of training variables is included in CrossFit modality training. Periodization is the process of prescribing exercise (and all associated variables) in a systematic fashion that reflects individualization, in an attempt to maximize progressive overload while balancing stress and recovery (Rhea, Alvar, Burkett, & Ball, 2003). There is an apparent conflict between the structured periodization of workout variables and current concepts of progressive overload in muscular fitness (Kraemer et al., 2002), compared to the central dogma of CrossFit: to “train for [unforeseeable challenges] by striving to keep the training stimulus broad and constantly varied” via “disinvest[ing] in any set notions of sets, rest periods, reps, exercises, order of exercises, routines, periodization, etc.” (Glassman, 2010)

Traditional Resistance Training

Traditional resistance training can be defined as exercise involving only one modality – weight training; gymnastics and metabolic conditioning exercises and workouts are typically not included in traditional resistance training sessions (Baechle & Earle, 2008; Ratamess et al., 2009). Such workouts are, instead, focused on working one or more groups of specific muscles (Baechle & Earle, 2008). A common practice in traditional resistance training is to alternate between workouts that predominantly target musculature found in the upper body and workouts that focus on working the muscles in the lower body; back to back performances of either 2 upper or 2 lower body workouts (that target the same muscle group(s)) are typically avoided in traditional training plans (Baechle & Earle, 2008).

Traditional resistance training workouts are also typically designed to include exercises that isolate specific muscles (rather than exclusively utilize “functional” compound movements), and most traditional resistance training programs organize training variables (e.g. reps/sets/rest time) in a fashion consistent with linear periodization (LP) models ((Prestes, De Lima, Frollini, Donatto, & Conte, 2009). LP models typically organize such variables to allow for a gradual increase of training intensity while simultaneously reducing training volume over the course of a training intervention (Rhea et al., 2003), and have been shown to elicit significant strength adaptations in an efficient manner (Chilibeck, Calder, Sale, & Webber, 1998; Kraemer et al., 2004).

High intensity techniques (i.e. supersets, dropsets, and pyramids) are commonly utilized during traditional resistance training as a method of progressive overload (Schoenfeld, 2011). Supersets involve performing 2 exercises back to back, without any rest period in between; dropsets involve completing one set of an exercise to muscular failure, immediately followed by another set of the same exercise at a lighter weight until muscular failure is reached again; sometimes, a third or "double dropset" is incorporated; utilization of the pyramid training technique requires the initial performance of high repetition, low load sets, with each set decreasing in repetitions while simultaneously increasing in load as the workout progresses (Schoenfeld, 2011).

The absence of circuits in traditional resistance training workouts does not permit the performance of long duration (i.e. > 2 minutes), sustained, continuous exercise; unlike CrossFit WODs, traditional resistance training workouts regularly include rest periods (typically > 60 seconds) between regular sets, supersets, or dropsets. This inclusion of rest potentially allows for a greater inter-set recovery period relative to CrossFit WODs (which actively discourage resting between sets).

Thus, despite the estimated billion dollar CrossFit industry and the popularity of CrossFit due its marketing as a superior method to enhance fitness, there is little empirical evidence to back these claims. Specifically, few experimental research projects have evaluated the efficacy of CrossFit training on the health and performance fitness attributes which CrossFit purports to improve (i.e. strength, endurance, power, stamina, flexibility, balance, speed, coordination, agility, and accuracy) (Glassman, 2010).

One published study (de Sousa et al., 2016) and one thesis (Jeffery, 2012) have empirically tested the effectiveness of CrossFit vs. traditional resistance training (based on subjective reports of participant training history in the previous 4-12 months) on select attributes of fitness (upper limb strength, cardiovascular endurance, and lower limb explosiveness) via a variety of field tests. However, both of these experiments were retrospective analyses of Crossfit versus traditional training; total training stress as well as specific exercise intensities, durations, types, were not controlled (or known to researchers) despite the fact all of these variables can have a significant impact on the aforementioned investigated fitness outcomes. Thus, the effectiveness of CrossFit vs. traditional modality resistance training cannot be fully justified based on their conclusions. Additionally, the findings of both of these studies are restricted to a limited number of fitness attributes, measured via field tests.

Collectively, the lack of control and limited field tests utilized in the aforementioned studies suggests that more detailed and in-depth investigations into the effects of CrossFit training on the magnitude and direction of adaptations in fitness are needed to justify this modality of training as a viable alternative to traditional resistance training for individuals who are not competitive CrossFit athletes. This is in agreement with the recommendations of a recent review article (Knapik, 2015) that reported a lack of empirically designed studies of CrossFit vs. traditional resistance on health, fitness, and performance. To date, only one published study (Barfield, Channell, Pugh, Tuck, & Pendel, 2012) had participants perform either a controlled CrossFit or traditional resistance training program (for multiple weeks), then compared the two groups for changes in body composition, as well as muscular endurance, strength, and power over time. However, because this study delivered both CrossFit and traditional resistance training workouts in accordance with the format of a "Basic Instruction Program" class, one could argue that the programming format advocated by the CFTG was violated; thus, future research comparing the effects of a traditional training program to a CrossFit training program (with workouts organized according to the official CFTG guidelines), is needed to determine the efficacy of the training modality created and distributed by CrossFit Inc.

To improve the rigor of the current study design, a "free exercise" control group was therefore utilized and asked to maintain their pre-study physical activity pattern and exercise regime. This approach ensured that changes in fitness that followed a periodized traditional resistance training program vs. a CrossFit program vs. habitual physically activity (when performed for equal durations of time) could be better understood.

Primary Purpose and Hypothesis

The primary purpose of the current study was to compare the effects of traditional resistance training, CrossFit, and a free exercise condition on changes in the following fitness outcomes: anaerobic and aerobic power, skeletal muscle endurance and strength, and energy metabolism. It was hypothesized that the CrossFit group would exhibit significantly greater increases in aerobic power (VO_{2max}), decreases in blood lactate concentration (at rest, during maximal exercise, and during recovery from maximal exercise), and increases in upper and lower body anaerobic power, as well as increases in upper and lower body muscular strength and endurance over time relative to both traditional and free exercise groups.

Secondary Purpose and Hypothesis

The secondary purpose was to examine the effect of CrossFit on the changes in fitness (between pre- and post-training). It was hypothesized that CrossFit and traditional modalities of resistance training would exhibit significant improvements in all aforementioned fitness outcomes measured post-training (relative to pre-training means).

Chapter 2: Literature Review

Introduction

CrossFit originated as a strength and conditioning program developed by coach Greg Glassman and his company, (CrossFit, Inc., Washington, DC); the goal of this program is to improve "work capacity across broad time and modal domains" (What is CrossFit?). CrossFit aims to accomplish this via training comprised of "constantly varied functional movements performed at relatively high intensity" (What is CrossFit?) - examples of CrossFit workouts can be seen in Appendix H. CrossFit is also an incredibly successful business, affiliating with more than 13,000 gyms and fitness centers around the world (Waryasz, Daniels, Gil, Suric, & Eberson, 2016; (What is CrossFit?). However, academic research on CrossFit is still quite limited – to date, studies examining this mode of exercise training generally investigates one of 3 questions: the effect of CrossFit training on acute physiological variables; the effect of CrossFit training on chronic physiological variables; or, the effect of CrossFit training on participant health (both psychological and physical).

In general, CrossFit researchers seem to agree that the sustained power output associated with this type of training is likely to promote improvements in VO_{2max} in recreational exercisers (Bellar, Hatchett, Judge, Breaux, & Marcus, 2015; Gerhart, 2014; Murawska-Cialowicz, Wojna, & Zuwala-Jagiello, 2015; Smith et al., 2013). However, others have reported decreases in aerobic fitness following short-term use of CrossFit training, suggesting that the high intensity nature of these workouts may lead to decrements in fitness if recovery is inadequate (Drake, Smeed, Carper, & Crawford, 2017; Outlaw et al., 2014). This is consistent with current research demonstrating mixed outcomes in multiple fitness attributes following regular use of the CrossFit training modality (Meyer, Sundaram, & Schafhalter-Zoppoth, 2017). Because empirical analysis of the effects of CrossFit on athletic populations has yet to be investigated, research examining the physiological outcomes of CrossFit have been limited to measuring relatively basic variables (e.g. heart rate, RPE, and body composition), with little to no association to performance outcomes in sport (Bellar et al., 2015; de Sousa et al., 2016; Fernández-Fernández, Sabido-Solana, Moya, Sarabia, & Moya, 2015; Mullins, 2015; Smith et al., 2013). The purpose of the following literature review is therefore to provide a summary of the currently known effects of CF training on physical fitness.

Energy Production for Exercise and Training Specificity

In order to understand how CrossFit modality training affects different aspects of physiology that are responsible for observable changes in fitness, one must first possess a basic knowledge of the physiological systems and pathways responsible for energy production during exercise; this information is crucial for understanding how and why different modalities of exercise affect different energy pathways, and how this manifests as observable changes in fitness over time. The following section is therefore a brief primer into the subcellular effects of exercise training; readers can use the information presented in the section below to apply subcellular training knowledge to CrossFit training characteristics (described in later sections).

Anaerobic energy is, by definition, derived from sources that do not require oxygen in order to be broken down; such metabolic substrates are eventually converted into adenosine triphosphate (ATP – a high energy molecule that, when split into adenosine diphosphate (ADP - an inorganic phosphate), produces energy for muscular contractions) (Gollnick et al., 1973). ATP stores in skeletal muscle are, however, extremely limited, and become rapidly depleted with the onset of exercise (Brooks, Fahey, & Baldwin, 2005; Dudley & Murray, 1982; McCafferty & Horvath, 1977; Sahlin, Tonkonogi, & Söderlund, 1998). Thus, another high energy molecule (creatine phosphate) begins to be used as a source of energy for muscular contractions before intramuscular ATP stores become fully depleted. Creatine phosphate (CP) is another metabolic substrate whose byproducts (after being broken down) can be utilized to resynthesize intramuscular ATP pools for approximately 20 seconds (Baldwin & Tipton, 1972; Gollnick et al., 1973; Karlsson & Saltin, 1970; Saltin, 1973). Collectively, the high energy phosphates ATP and CP can therefore be used as acute sources of energy for muscular contraction to power maximal intensity exercise for approximately 20-30 seconds in duration, before becoming completely depleted (Brooks et al., 2005; Dudley & Murray, 1982; Sahlin et al., 1998); because the breakdown of both of these molecules does not require the presence of oxygen, energy from this system is considered to be anaerobic in nature, and used as the predominant source of energy for non-continuous, short duration, high intensity exercise.

Once exercise induced depletion of muscular ATP and CP reaches a certain threshold, another anaerobic process takes over to continue supplying ATP for skeletal muscle contraction. As classic studies in exercise physiology have demonstrated, anaerobic glycolysis (i.e. metabolism of glucose to produce ATP, without the use of oxygen) is initiated prior to the complete depletion of ATP and CP (Saltin, 1973); this serves as the predominant source of energy during sustained submaximal to maximal intensity, lasting approximately 60 – 180 seconds in length (Brooks et al., 2005; Dudley & Murray, 1982; Sahlin et al., 1998).

As the duration of continuous exercise increases, a shift from predominantly anaerobic energy sources (i.e. metabolic reactions that create ATP without the use of oxygen) to predominantly oxidative energy sources occurs; this phenomenon continues to occur until most of the energy required for muscular contraction can be sustained through oxidative processes (Keul, 1973). The resulting decreased reliance on anaerobic energy sources is due to increased ATP production in a subcellular organelle known as the mitochondria – within this structure, ATP is synthesized rapidly though the oxygen mediated metabolism of both carbohydrate and fat substrates (Brooks et al., 2005; Dudley & Murray, 1982; McCafferty & Horvath, 1977; Sahlin et al., 1998). However, the relative contribution of these substrates to energy production for skeletal muscle contraction is dependent on both the intensity and duration of the exercise performed.

During low intensity exercise that is sustained for a prolonged period of time, free fatty acids serve as the predominant energy source for muscular contractions; conversely, when high intensity exercise is performed for a few minutes only, the metabolism of fat substrates plays a nearly negligible role in the production of energy (Paul & Holmes, 1975). This in line with bioenergetics research in the exercise physiology domain, which has historically found that during prolonged exercise, levels of glycogen (a carbohydrate substrate) decrease as the level of free fatty acids in the blood tends to increase (up to 5-6 fold resting levels) (Keul, 1973; Keul, Doll, & Keppler, 1972). This is because a shift from carbohydrate to fat metabolism occurs in working muscles during long periods of continuous exercise; when combined with the increased mobilization of free fatty acids from adipose tissue that occurs during exercise, the result is increased free fatty acid uptake by the muscle cells (Keul, Haralambie, Arnold, & Schumann, 1974; Paul & Holmes, 1975). Because free fatty acids circulating in the blood can be rapidly oxidized (and subsequently metabolized in the mitochondria of skeletal muscles cells to make ATP), free fatty acids serve as a major fuel source for muscle contractions when low intensity exercise is prolonged (McCafferty & Horvath, 1977; Paul & Holmes, 1975).

Conversely, when submaximal exercise intensity is sustained for multiple minutes, glycogen predominates as the main source of fuel for muscular contractions (Bergström & Hultman, 1967). In fact, exercise at 60-80% of VO_{2max} can lead to near or total depletion of muscle glycogen stores, if sustained for a long enough duration (Bergström & Hultman, 1967; Hermansen, Hultman, & Saltin, 1967; Taylor, 1973) – this may, subsequently, lead to fatigue, as research has demonstrated that a reduction in work capacity typically follows glycogen depletion (Ahlborg, Bergström, Ekelund, & Hultman, 1967; Bergström & Hultman, 1967). Glycogen depletion mediated fatigue may therefore be postponed if the body begins to use free fatty acids for energy production sooner in the exercise bout; this would reduce the dependence of the body on carbohydrate substrates to provide sufficient energy for continuous muscular contractions, thereby preserving intramuscular glycogen stores (Holloszy, 1975; McCafferty & Horvath, 1977; Paul & Holmes, 1975).

Given these findings, it is apparent that the type, duration, and intensity of physical activity performed determines the energy source predominantly used to generate muscular contractions during exercise (McCafferty & Horvath, 1977; Morris, McCafferty, & Edington, 1974a; Morris, McCafferty, & Edington, 1974b). Furthermore, bioenergetic adaptations to exercise appear to be specific to the training used, with metabolic characteristics of the imposed exercise demands potentially determining the predominant energy source used to produce energy for the working muscle (Morris et al., 1974a; Morris et al., 1974b); thus, adaptations in fitness that follow exercise training will be specific to the training stress applied and the energy systems utilized (McCafferty & Horvath, 1977).

Adaptation to Exercise and Training Stress

In order for physiological adaptations to follow exercise training, the exercise performed must produce a large enough physiological stimulus to disrupt the homeostasis of the subcellular metabolic systems that supply fuel for muscular work; the human body has been shown to adapt to such disruptions in homeostasis by inducing changes in physiological and metabolic processes that make the body more resistant to the same type, duration, and intensity of exercise stress the next time it is encountered (McCafferty & Horvath, 1977). This theory is based on the general adaptation syndrome model (Selye, 1950), and suggests that in order to elicit continuous adaptations in fitness, exercise training must progressively overload the physiological systems of the trainee. In other words, once the body has adapted to a specific exercise stress, repetitive use of the same stress will not incur further adaptations in exercise physiology (and may lead to stagnation or even regression in previous adaptations), because the lack of progressive overload will prevent the exercise stress from disrupting homeostasis of the subcellular metabolic process (Castelli, 2017; Coffey & Hawley, 2007; Reilly, Morris, & Whyte, 2009). Other researchers have built on this concept, demonstrating that a period of "super-compensation" can follow sustained training if the training stress incurred is sufficient to progressively overload the trainee; during this period, adaptations specific to the duration, intensity, and type of exercises performed can occur if a deload in training stress is observed following the sustained period of progressive overload training (Yakovlev, 1975). More modern researchers have added even further specifications to this exercise adaptation theory, suggesting that super compensation (and the resulting adaptations), will only occur if the training stress is below the individual's maximal recoverable volume (MRV) during the de-load period (Castelli, 2017).

The MRV theory proposes that each individual has a maximum amount of training volume from which they can recover (Castelli, 2017); if training volume regularly exceeds this threshold, this theory asserts that the individual may enter a physiological state known as "over-reaching", in which an individual will not experience any increases in performance, and may even experience regressions in performance if the resistance training stimulus is too high (i.e. training volumes/intensities are unmanageable). "Non-functional over-reaching", results when sustained periods of over-reaching eventually lead to decrements in athletic performance, fitness, as well as mental and/or physical health (Armstrong & VanHeest, 2002; Bushie & Lobe, 2007; van Borselen, Vos, Fry, & Kraemer, 1992). Prolonged decrements in these variables typically result in a negative physiological condition known as the “over-training syndrome” (OTS); this is a critical condition that can be incredibly detrimental to an individual, as physiological decrements associated with OTS can take multiple months before returning to normal levels (Armstrong & VanHeest, 2002; Bushie & Lobe, 2007; Fry & Kraemer, 1997; Lemyre, Roberts, & Stray-Gundersen, 2007; Stone et al., 1991; Urhausen & Kindermann, 2002; van Borselen et al., 1992). Symptoms most commonly associated with OTS include sustained increases in resting heart rate, persistent muscle soreness and pain, as well as decreases in sport performance, maximal power output, and muscular strength; disruption in sleep patterns, persistent illness, a decreased motivation to train, and frequent irritability have also been cited as symptoms of OTS (Armstrong & VanHeest, 2002; Fry & Kraemer, 1997; Stone et al., 1991; Urhausen & Kindermann, 2002; van Borselen et al., 1992). Conversely, if the level of training volume is well below one’s MRV, the stimulus induced by the training will not be sufficient to disrupt the homeostasis of the physiological systems that govern power production for exercise (Castelli, 2017; Drake et al., 2017); therefore, no super-compensatory period or adaptations to the training stress will occur, regardless of whether or not a deload period is included following progressive overload training. Optimal training is thus a careful balance between training near enough one’s MRV to incur adaptations to exercise stress, while also ensuring recovery is sufficient to prevent non-functional over-reaching, and potentially resulting OTS (Drake et al., 2017).

Concurrent Training

Because most sports require a combination of aerobic and anaerobic cardiovascular power, as well as musculoskeletal fitness, finding physical training programs that improve all of these variables in the most time-effective manner is the desire of many sport scientists, coaches, and athletes alike. Concurrent training that combines both endurance and strength exercise is consequently gaining increasing interest from the academic community as a method of combatting limited athlete time and availability for training.

Significant improvements in musculoskeletal strength and aerobic endurance have traditionally been thought to occur following training at opposite ends of the spectrum (i.e. high load and low repetition vs. low load and high repetition exercise) (Hickson, 1980; Leveritt, Logan, Abernethy, & Barry, 2003; J. Wilson et al., 2012), with strength development being negatively affected by concurrent training (when compared to resistance training performed in the absence of endurance training) (Fyfe, Bishop, & Stepto, 2014; J. Wilson et al., 2012).

For the purposes of this paper, strength training can be defined as the performance of multiple sets of exercises consisting of loaded movements against an external resistance (i.e. barbells, dumbbells, machines, or other equipment found in typical fitness center settings) (Bazyler, Abbott, Bellon, Taber, & Stone, 2015). Strength training involves exertion of high intensity force (typically achieved using loads at 70-100% of an individual's 1 repetition (rep) maximum (1RM)), at low velocities, against an external resistance (Andersen & Aagaard, 2010; Bompa & Haff, 2009; Stone, Stone, & Sands, 2007).

For the purposes of the current paper, endurance training differs significantly from strength training, and can be defined as exercise including higher repetitions, and primarily unloaded movements, resulting in a heightened response from the aerobic (rather than anaerobic) energy system (Tanaka & Swensen, 1998); endurance training is also performed with the intent of improving long term work capacity, rather than rate of force development (Tanaka & Swensen, 1998).

When isolated from one another, endurance and strength training modalities induce adaptations that appear at opposite ends of the training-adaptation spectrum (Coffey & Hawley, 2017). The molecular mechanisms behind these training induced changes have been investigated extensively by other authors (Coffey & Hawley, 2007; Coffey & Hawley, 2017; Nader et al., 2014; Nader, 2006; Reilly et al., 2009).

Briefly, the use of repetitive or continuous bouts of exercise (comprised of submaximal muscular contractions) lasting longer in duration (i.e. 60 minutes or more) has been hypothesized to improve endurance performance through training mediated increases of fast-to-slow muscle fiber type conversion, production of mitochondria, as well as shifts in exercise metabolism towards the predominant breakdown of fat substrates (rather than carbohydrate sources) to fuel muscular contractions (Hawley, 2002; Holloszy & Coyle, 2016). Collectively, these adaptations have been said to improve endurance performance by promoting enhancements in oxidative capacity (i.e. training induced development in the cellular structures that regulate oxidative metabolism) (Coffey & Hawley, 2017).

Conversely, improvements in musculoskeletal strength have been shown to follow exercise of considerably shorter durations (60 seconds or less), comprised of muscular contractions at maximal intensities (elicited through heavy load resistance training) (Damas, Phillips, Vechin, & Ugrinowitsch, 2015). The physiological mechanisms responsible for improvements in strength are also markedly different, consisting of enhanced myofibrillar protein synthesis (and subsequent muscular hypertrophy) with little to no change in fat vs. carbohydrate metabolism during exercise, or the oxidative capacity of trained muscles (Coffey & Hawley, 2007; MacDougall, Sale, Elder, & Sutton, 1982; Nader et al., 2014; Reilly et al., 2009).

Strength Training and Muscle Fiber Architecture

Researchers have previously categorized muscle fibers based on characteristics of muscle proteins (namely myosin) that comprise each muscle fiber (Andersen & Aagaard, 2010). Although recent advancements in histochemical staining techniques have allowed researchers to identify 7 distinct varieties of muscle fibers in human skeletal muscle (Scott, Stevens, & Binder-Macleod, 2001), most of the research on muscle fiber physiology to date (especially regarding the effects of training) has focused on 3 different fiber types (J. Wilson, Loenneke et al., 2012). Given the fact that academic literature investigating the effects of CrossFit training is also fairly limited, this thesis will focus on the 3 most researched types of muscle fibers (and their respective physiological architecture), in order to better identify potential mechanisms for findings of the current experiment.

Myosin (in particular, the heavy chain of the myosin molecule, MyHC) exists in 3 different forms (known as isoforms – different versions of the same protein that perform the same function): MyHC1, MyHC2a, and MyHC2x (Andersen & Aagaard, 2010). Contraction velocity of each muscle fiber is largely determined by isoform dominance within the fiber - fibers comprised primarily of MyHC1 are slower to contract (and hence, often referred to in the literature as slow/type 1 muscle fibers) than those comprised primarily of MyHC2a (commonly referred to as fast/type 2a muscle fibers), which are slower to contract than MyHC2x dominant fibers (also known as fast/type 2x muscle fibers) (Bottinelli, 2001; Harridge et al., 1996). Others have reported the relative contractile velocity of type 2x: 2a: 1 muscle fibers as 4.4: 3: 1 (Malisoux, Francaux, Nielens, & Theisen, 2006).

Additionally, different muscle fiber types seem to derive energy for contractions from different metabolic sources, with previous researchers categorizing fiber types according to their predominant source of energy. While type 1 fibers (i.e. slow-oxidative fibers) predominantly derive energy from oxidative metabolism, type 2x fibers (i.e. fast-glycolytic fibers) derive energy predominantly from anaerobic glycolysis. Conversely, type 2a fibers (i.e. fast-glycolytic-oxidative fibers) derive energy from a combination of both anaerobic and aerobic sources of metabolism (J. Wilson et al., 2012).

According to the work of Bottinelli, Pellegrino, Canepari, Rossi, and Reggiani (1999), the maximum force and power that can be produced by a single muscle fiber is largely determined by its content of fast (i.e. type 2a or 2x) myosin (Bottinelli, Pellegrino, Canepari, Rossi, & Reggiani, 1999). These conclusions support an older body of muscle fiber research, which demonstrates a strong relationship between muscle fiber composition and whole muscle contractile velocity (Aagaard & Andersen, 1998; Harridge, 1996; Harridge et al., 1996; Tihanyi, Apor, & Fekete, 1982; Yates & Kamon, 1983). Collectively, this literature suggests that individuals with higher proportions of fast muscle fibers (i.e. high MyHC2x/2a content) will be able to achieve greater muscle force output, especially during fast movements (such as acceleration phases of propulsion during sprinting) than individuals with lower proportions of fast fibers (Andersen & Aagaard, 2010). Similarly, the work of Harridge et al. (1996) suggests that muscles comprised of greater proportions of fast muscle fibers may exhibit substantially higher rates of force development (thereby exhibiting greater power output/explosiveness) than muscles comprised of greater proportions of slow fibers (Harridge et al., 1996). This theory is supported by a more recent study by Widrick et al. (2002), which demonstrated that when isolated, the ratio of peak power output of type 2x: 2a: 1 muscle fibers is 10:6:1 (Widrick, Stelzer, Shoepe, & Garner, 2002).

Strength training has been shown to elicit a shift in type 2x to type 2a muscle fibers (Adams, Hather, Baldwin, & Dudley, 1993; Andersen & Aagaard, 2000; Folland & Williams, 2007; Fry, 2004; Hather, Tesch, Buchanan, & Dudley, 1991). These changes have been previously hypothesized to enhance the late race sprint capacity of endurance athletes through reserving muscle fibers with the fastest possible contraction velocity (i.e. type 2x) during earlier stages of competition. The idea of preferential muscle fiber recruitment related to greater fiber proportionality has been briefly explored in previous literature; if a greater relative proportion of type 2a fibers delays recruitment of less prominent type 2x muscle fibers, force output could be maximized at latter stages of endurance sport races (assuming adequate substrate stores support such activity) by reserving muscle fibers with the fastest possible contraction velocity (i.e. type 2x) throughout competition (Morgan et al., 1995; Tanaka & Swensen, 1998).

Endurance Training and VO2$_{max}$

Significant increases in VO_{2max} with time is a training adaptation consistently induced via endurance training (Pescatello, 2014). Endurance training has been shown to elicit increases in the number and size of mitochondria in skeletal muscle fibers as well as the activity of enzymes involved in the aerobic degradation of ATP from fat and carbohydrate substrates; both of these can result in increased production of energy for exercise through the aerobic pathways (Green, Barr, Fowles, Sandiford, & Ouyang, 2004; Hoppeler & Flueck, 2003; Starritt, Angus, & Hargreaves, 1999). Endurance training has also been found to induce hypertrophy of the heart (specifically in the left ventricle, an adaptation which, in turn, increases the amount of blood leaving the heart with each contraction (i.e. enhanced cardiac output through increased stroke volume)), thereby enhancing the delivery of oxygen (dissolved in blood) to exercising muscles, and subsequently increasing VO_{2max} (Moore & Palmer, 1999).

Other authors have shown that plasma volume increases of up to 20% can follow endurance training (Sawka, Convertino, Eichner, Schnieder, & Young, 2000); this adaptation has been thought to increase VO_{2max} thorough enhancing stroke volume and oxygen transport (Goodman, Liu, & Green, 2005; Hagberg et al., 1998). Adaptations in addition to increased plasma volume (such as enhanced circulatory reserve, increased end-diastolic volume, and temperature regulation during exercise) may also contribute to aerobic fitness improvements following endurance type training (Goodman et al., 2005; Hagberg et al., 1998).

Another theory purports that enhanced capillarization improves oxygen delivery to muscles, and this is what causes an increase in VO_{2max} following sustained endurance training. This theory is supported by the work of Murawska-Cialowicz et al. (2015) who also reported significant improvements in aerobic power (14% increase in VO_{2max}) following CrossFit training (Murawska-Cialowicz et al., 2015). These authors hypothesized that a training induced increase in the partial pressure of oxygen (pO2) in the blood stream contributed to an increased saturation of oxygen in the blood (following exercise and during rest); when combined with the fact that expression of vascular endothelial growth factor (VEGF) increases in the brain, lungs, and skeletal muscles during physical exertion (Tang, Xia, Wagner, & Breen, 2010), these findings suggest that CrossFit may improve aerobic power through 1. enhanced oxygen saturation of circulating blood; and 2. improved delivery of this oxygen rich blood to exercising muscles.

CrossFit as a Method of Concurrent Training

Although still quite sparse in the literature, a few studies investigating the effects of CrossFit on physiological outcomes have demonstrated that this multimodal type of training can elicit improvements in both aerobic and anaerobic fitness outcomes (Meyer et al., 2017; Outlaw et al., 2014). Additionally, research has demonstrated that CrossFit training can also improve body composition in healthy adults ranging in initial fitness levels (Murawska-Cialowicz et al., 2015; Smith et al., 2013), as well as enhance aerobic and anaerobic factors critical for success in CrossFit competition and superior performance during CrossFit workouts (Bellar et al., 2015). Consequently, authors have previously suggested that CrossFit can be considered as a viable method for performing concurrent strength and endurance training (de Sousa et al., 2016).

One study to date has assessed the oxidative stress of CrossFit training; Kliszczewicz et al. (2015) examined the blood plasma of 10 male adults (26.4 ± 0.9 years) who all had a minimum of 3 months of CrossFit training experience (prior to study initiation) (Kliszczewicz et al., 2015). Comparisons of oxidative stress biomarkers in the plasma of participants were made after performing the CrossFit WOD "CINDY" (i.e. as many rounds possible of 5 pull-ups, 10 push-ups, and 15 body-weight squats in 20 min), and after performing a bout of high-intensity, continuous treadmill running (i.e. 20 minutes of running at a "comfortable" speed, with the incline regularly adjusted to maintain participant heart rate at 90% of pre-determined maximum). Interestingly, these authors found that the oxidative stress induced by the CrossFit WOD was similar to the oxidative stress of continuous, high intensity running.

The continuous and sustained nature (i.e. >3 minutes in duration) of the treadmill running bout utilized in the study by Kliszczewicz et al. (2015) reflects a modality of exercise typically included in bouts of endurance training, but not during strength focused training. These findings agree with the work of others regarding the high aerobic demand placed on individuals performing CrossFit workouts (Farrar, Mayhew, & Koch, 2010; Fernández-Fernández et al., 2015; Kliszczewicz, Snarr, & Esco, 2014; Murawska-Cialowicz et al., 2015; Pollock et al., 1998; Smith et al., 2013; Zagdsuren et al., 2015) and collectively suggest that CrossFit training may produce a training stress similar in nature to a bout of endurance training, rather than a bout of strength training; consistent performance of CrossFit workouts should therefore theoretically interfere with gains in muscular strength that normally follow heavy resistance training (when performed in isolation of endurance type training) (Fyfe et al., 2014; J. Wilson et al., 2012).

Thus, as with any type of concurrent training, sport scientists and fitness practitioners must consider the possibility of a physiological phenomenon known as the "interference effect" negatively impacting participant power and/or strength outcomes following prolonged CrossFit training (Hickson, 1980). Although some authors have shown that that concurrent training can improve endurance outcomes (Beattie, Kenny, Lyons, & Carson, 2014; Paton & Hopkins, 2004), these improvements may come at the expense of limitations in both explosive power and maximal musculoskeletal strength enhancements (Coffey & Hawley, 2017; de Sousa et al., 2016). However, it is still unclear if the interference effect is a reasonable cause for concern in individuals interested in practicing CrossFit. Some studies have shown that, when compared to a traditional resistance training program, concurrent training can negatively affect strength and power development (Fyfe et al., 2014; J. Wilson et al., 2012), but these conclusions conflict with other studies examining the same phenomenon (Apró, Wang, Pontén, Blomstrand, & Sahlin, 2013; Apro et al., 2015; Carrithers, Coker, Sullivan, Carroll, & Trappe, 2007; Coffey et al., 2009; Lundberg, Fernandez-Gonzalo, Gustafsson, & Tesch, 2012; Murach & Bagley, 2016).

Furthermore, there is an apparent gap in the sports science literature regarding the effect of combining multiple training modalities within single training sessions (as is customary during CrossFit WODs) on participant fitness. To date, research examining the effect of concurrent training on both strength and endurance outcomes have been mostly limited to interventions that isolate cardiovascular exercise from resistance training exercise, either by placing workouts focused on improving these attributes on different days, or on different workouts (separated by multiple hours) within the same day (Beattie et al., 2014; Paton & Hopkins, 2004).

Although one study has compared differences in physical fitness between recreational individuals who regularly perform CrossFit workouts, to those who regularly perform traditional resistance training (de Sousa et al., 2016), the conclusions of this study has limited application, given the fact that the authors utilized an observational research style, as opposed to prescribing specific exercise programs. Due to the consequential lack of control over participant training exercise variables (such as exercises, equipment, repetition, rest, and set schemes), and the fact that researchers in this study did not collect training journals or any other means of tracking individual workouts (prior to surveying participants), it is still unclear whether or not concurrent style training that combines anaerobic, aerobic, and strength training into single workouts has any benefit over traditional resistance training programs. Additionally, because academic research on CrossFit training is still relatively sparse, no studies to date (to this author's knowledge) have performed specific investigation into the physiological mechanisms behind the previously reported improvements in aerobic power, anaerobic fitness, and body composition associated with this mode of exercise.

Acute and Prolonged Effects of CrossFit Training

A recent study examining the acute effects of CrossFit training on perceptual and physiological response to exercise (Fernández-Fernández et al., 2015) found that, in healthy, middle-aged subjects with approximately 1 year of CrossFit training experience, the CrossFit WODs "FRAN" and "CINDY" elicit significant cardiovascular responses; FRAN is a WOD comprised of barbell front squat and overhead press (i.e. "thruster") and pull-up exercises, performed back to back; there are 3 rounds to this WOD, with participants required to perform 21 repetitions of each movement, then 15 repetitions, then 9 repetitions, as quickly as possible. No rest time is prescribed between movements, or between rounds. Conversely, the WOD CINDY involves performing 5 pull-ups, followed by 10 pushups, followed by 15 body weight squats, back to back; participants are expected to complete as many rounds of this circuit as possible, in 20 minutes. As with FRAN, no rest is prescribed between exercises or circuits completed during CINDY. On average, participants in this study reached 61.5% of VO_{2max} and 96.4% of their maximal heart rate (HRmax) while performing these CrossFit WODs (respectfully). These findings exceed the minimum requirements for promoting aerobic fitness in adults, previously established by the ACSM (Garber et al., 2011).

Smith et al., (2013) examined the effects of a prolonged CrossFit intervention on the physiological variables of participants. Following 10 weeks of performing CrossFit WODs at a frequency of 5 days per week, the average relative VO_{2max} of all male participants increased by 5.86 $ml \cdot kg^{-1} \cdot min^{-1}$ (a 14% increase relative to baseline), and the average VO_{2max} of all female participants increased by 4.24 $ml \cdot kg^{-1} \cdot min^{-1}$ (a 12% increase relative to baseline); within the same time period, the average body fat percentage of participants dropped by dropped from 22.2% to 18.0% (in men) and from 26.6% to 23.2% (in women) overtime.

The participants in this study (n = 43) were recruited on a voluntary basis from a single CrossFit gym, and exhibited a wide range of pre-intervention aerobic fitness levels (20 - 58 ml·kg^{-1}·min^{-1} VO_{2max}) and body compositions (10.7 - 46.1 % body fat). With regards to the impact of prolonged CrossFit training on aerobic fitness, the findings of Smith et al. (2013) demonstrate an increase in VO_{2max} from pre- to post-intervention, even in participants possessing VO_{2max} values well above average. This suggests that CrossFit modality training may be a useful alternative for endurance athletes wishing to improve an already elevated aerobic fitness profile.

Thus to date, research examining the effects of CrossFit training on physiological variables has established that CrossFit WODs acutely elicit a cardiovascular response which exceeds the minimum requirements for improving aerobic fitness in adults (published by the ACSM). This explains why, over multiple months, CrossFit training has been shown to significantly improve aerobic fitness and across recreational exercisers with a wide range of initial fitness levels and training experience.

Chapter 3: Methods

Location

This study was conducted at the University of Alberta (Edmonton Alberta, Canada). Recruitment, training, and storage of study participant data occurred within the University's Van Vliet Complex. During the study, off campus communication with participants was performed through email (as necessary). This study was approved by the Research Ethics Office of the University of Alberta (identification number: Pro00072960).

Participants

Participants were females and males (aged 18-30) recruited (on a voluntary basis) from the local University and Edmonton area community. Recruitment was performed using posters (posted in and around the Van Vliet Center (VVC) – see Appendix J); individuals expressing interest in participating in the study contacted the primary investigator (via email) to schedule an initial fitness assessment. Upon initial contact, potential participants were sent an email (from the primary investigator) containing an information letter discussing the procedures, timeline, level of commitment, potential risks and benefits of the current study, as well as inclusion criteria (see Appendix K).

Inclusion criteria for participants included: 1. Performance of regular (≥2x per week) exercise training (comprised of both aerobic and resistance training) for ≥ 6 months (prior to study initiation); the criteria of habitual exercise training for ≥6 months was included to reduce the large influence of neural factors associated with increases in strength and muscle power in non-strength trained individuals; the age range of participants was chosen to increase the likeliness of obtaining the required number of participants for each group, from the University of Alberta community. Participants who responded to the information letter gave informed consent for their participation in the study via waiver (see Appendix K) and confirmed that they met both tenants of the aforementioned inclusion criteria. Participants who were currently injured, or had sustained an injury recently that would have compromised their ability to perform exercise were not permitted entrance into the study.

Thirty participants were recruited based on a recent body of literature that investigated the effects CrossFit and rock climbing on physiological outcomes (Fernández-Fernández et al., 2015; Hermans, Andersen, & Saeterbakken, 2017; Laffaye, Collin, Levernier, & Padulo, 2014; Smith et al., 2013; Stankovic, Ignjatovic, Rakovic, Puletic, & Hodžic, 2014); sample sizes in these studies ranged from 10-43 participants, with an average of 29.8 subjects/study. Given these previous research sample sizes, 10 participants per group was the recruitment goal.

Study Design

Upon successful recruitment, participants were randomly assigned to one of three groups (FE, TRAD, and CF). Participants in the TRAD and CF groups then performed 6 weeks (at a maximum frequency of 4 training sessions per week) of supervised traditional resistance training or CrossFit training workouts, respectfully. The 6-week training period for both TRAD and CF in the current study is similar in duration to other CrossFit training interventions previously used in the literature (Barfield et al., 2012; Drake et al., 2017; Eather, Morgan, & Lubans, 2016; McKenzie, 2015; Paine, Uptgraft, & Wylie, 2010; Sobrero et al., 2014). Additionally, previous studies have confirmed that significant improvements in strength, power, and endurance can be detected in training interventions lasting 6 weeks or less across a wide variety of populations (Brown et al., 2017; Gacesa, Jelena, Klasnja, & Grujic, 2013; Manca et al., 2017; Negra et al., 2016), regardless of the periodization structure utilized to organize exercise variables (Pelzer, Ullrich, & Pfeiffer, 2017).

Participants assigned to the FE group were asked to maintain their pre-study exercise habits during the 6-week study period. Individuals assigned to the TRAD and CF groups were asked to refrain from participating in structured resistance training workouts outside of project prescribed sessions and to record additional physical activity performed during the 6-week study period (i.e. non-supervised workouts and exercise bouts that included aerobic, flexibility, and/or team sport components). The FE group was asked to record all physical activity that was recognized as a "workout"; this term can be defined (as described to FE participants) as a pre-planned bout of physical exertion above resting levels, consistent with ACSM recommendations for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults (i.e. moderate-intensity cardiorespiratory exercise for ≥30 minutes, vigorous-intensity cardiorespiratory exercise training for ≥20 minutes, or a combination of moderate- and vigorous-intensity exercise to achieve a total energy expenditure of ≥500-1000 MET·min·wk) (Garber et al., 2011).

Physical activity data for all groups was self-logged in individual digital exercise diaries (distributed to password protected Google Drive accounts by the research team) upon study initiation, and for the entirety of the 6 week study period (see Appendix L). This provided the ability to not only quantify the total amount of stress for the prescribed intervention workouts (TRAD and CF) but also the global amount of activity done by each participant in each group. Consequently, knowledge of the specific durations and types of exercise performed during the study intervention allowed the research team to determine if significant differences in training adaptations and/or outlying baseline/post-training test values could be attributed to differences in the controlled training stress (i.e. planned TRAD vs. CF workouts), or other, confounding exercise variables (external to researcher control). Furthermore, researchers compared differences in the amount of time spent training in each relative intensity "zone" (i.e. light, moderate, and vigorous) over the course of the study duration; between group differences in accumulated training intensities were therefore also evaluated as a potential explanation for findings of the current experiment.

Training: Free Exercise Group

Individuals assigned to FE were asked to maintain their pre-study training and exercise habits for the 6 week study period. In this sense, no manipulation of training occurred for the FE group –therefore, the results precipitated from this group could be used to understand how an absence of training manipulation (i.e. not performing the novel CrossFit or traditional resistance training programs used in the current study) affects fitness in recreationally active adults. Consequently, FE acted as the control group (with respect to controlling for an absence of traditional or CrossFit modality training), and the change in fitness outcomes of FE was subsequently compared against the other two study groups.

Training: CrossFit Group

The 6-week training intervention for individuals in the CF group was derived from the multiple week CrossFit programs previously used to train individuals in academic studies (Drake et al., 2017; Paine et al., 2010), and followed the programming recommendations presented in the CFTG, (Glassman, 2010). Both Drake et al. (2017) and Paine et al. (2010) utilized training interventions comprised of a wide variety of exercises (participants were often performing different exercises every workout); additionally, training sessions in these studies consisted of a combination of gymnastics movements (e.g. handstands, ring work, and bar exercises), compound loaded exercises (e.g. barbell squat, barbell deadlift, overhead press), and unloaded cardiovascular exercise (e.g. box jumps, skipping, running). CrossFit workouts in the current study incorporated these characteristics, as well as mimicked the training session layouts utilized by Drake et al. (2017) and Paine et al. (2010) via performance of warm-up, strength/skill, and WOD components (in that order).

Warm-up sets were completed for each exercise, during every workout, to ensure that the prescribed number of repetitions were always performed with a maximal effort intensity – additionally, participants were instructed to choose loads that elicited a 9-10 rating (on the Borg CR-10 scale) during the last repetition of each set.

During all training sessions, CF participants performed CrossFit workouts with a partner (i.e. another participant randomly assigned to the CF group); all sessions were actively supervised by a Canadian Society of Exercise Physiology (CSEP) certified personal trainer (who demonstrated and monitored correct exercise form), who was either the primary investigator, an individual with a PhD in exercise science, or an individual possessing an undergraduate kinesiology degree and multiple years of experience in personal training. All training of CF participants occurred in a CSEP certified fitness facility (the University of Alberta Hanson Fitness and Lifestyle Center) with qualified personnel available at all times to answer questions or supervise specific exercises.

As CrossFit does not utilize periodization of training variables, the number of sets and reps for each exercise in the WOD differed for every workout. No isolation exercises were used during CrossFit WODs. Instead, only movements involving the contraction of multiple muscle groups and movement of multiple joints simultaneously were performed by CF participants; these included: deadlift, handstand pushups, pull-ups, thrusters, pushups, squats, kettlebell swings, box jumps, wall balls, burpees, hang cleans, front squats, back squats, standing shoulder press, tricep brachii dips, and overhead squats – all exercises were performed using either participant bodyweight or free weights (i.e. dumbbells, barbells, and kettlebells). CrossFit WODs were also performed with an emphasis on speed; CF participants were always asked to perform exercises at a maximal intensity, such that no rest was prescribed between exercises or between circuits; WODs were therefore either performed for as many rounds as possible in 12-20 minutes, or with the goal of completing all prescribed sets and repetitions as fast as possible. More detailed set, repetition, and exercise prescription information for workouts performed by the CF participants can be found in Appendix H.

Training: Traditional Group

The 6-week training program for individuals assigned to the TRAD group was derived from previous studies investigating periodization models in traditional resistance training programs (Ebben et al., 2004; Prestes et al., 2009) - these prescriptions are consistent with the National Strength and Conditioning Association (NSCA) guidelines for athlete development (Baechle & Earle, 2008), and utilize a low variety of exercises, repeated every week (unlike in the CF protocol, where most exercises varied from week to week).

Similar to participants in CF, TRAD participants completed a warm-up process for each exercise, every workout, such that the prescribed number of reps were always performed with a maximal effort intensity – this effort was ensured by instructing participants to choose loads that elicited a 9-10 rating (on the Borg CR-10 scale) during the last repetition of each set. Individuals undergoing TRAD training also performed workouts in partners; TRAD participants completed a two-on-one personal training session with a CSEP certified personal trainer (who demonstrated and monitored correct exercise form), or other member of the research team with the minimum aforementioned qualifications.

Training variables (e.g. reps/sets/rest time) in the TRAD program were organized in a fashion consistent with linear periodization (LP) models, whereby the first week of training involved performing all sets to failure at 12-14 repetitions, with target repetitions decreasing each week (to a minimum of 4-6 repetitions per set) in a time-dependent fashion. Two workouts (targeting predominantly upper body musculature on the first day, and lower body musculature on the second day) were performed in an alternating fashion each training session. These workouts were comprised of both isolation and compound exercises, including: flat bench press, incline chest fly, seated shoulder press, standing lateral shoulder raise, cable triceps brachii extensions, seated bicep brachii curls, leg press, squat, deadlift, prone hamstring curl, seated quadricep extension, seated calf press, and seated latissimus dorsi pull down; exercises were performed using a combination of free weights, cables, and machines. Specific examples of TRAD workouts can be found in Appendix I.

It is plausible that habituation in TRAD participants to more traditional forms of resistance training had likely already occurred to some degree prior to the initiation of training (as a consequence of the recruitment criteria requiring previous weight training), meaning that a greater training stimulus would be required to induce further resistance training mediated improvements in fitness. Conversely, it is likely that the CrossFit workouts used in the current study differed more from the previous training regimens used by CF participants; therefore, this mode of resistance training included a wealth of what were probably novel training stimuli for the CF participants. In an attempt to limit such stimuli as a confounding variable, TRAD participants were also asked to perform high-intensity techniques (i.e. supersets, dropsets, and pyramids) as a means of providing additional progressive overload. It was hoped that gradual incorporation of these techniques into traditional workouts (with easier techniques such as supersets, occurring earlier in the training program) would provide enough of a training stimulus overload in TRAD to reflect the novel training stimuli encountered by CF participants.

Unlike CrossFit WODs, traditional resistance training workouts in the current study did include prescribed rest periods between each set (or superset) of exercises performed; specific rest times and other workout variables (e.g. sets, reps, and exercises) within each traditional workout performed can be found in Appendix I.

Pre-Screening

Upon successful acceptance into the study (and prior to any testing session), each participant was screened for heart rate, blood pressure, and other health risks according to the Physical Activity Readiness Questionnaire (PAR-Q). This document is recommended by CSEP as a standard screening measure for apparently healthy adults prior to participation in exercise interventions or assessments. During this time, participant body weight was also measured – this metric was used to determine participant specific test protocols and analyze resulting data in the following tests.

Testing

Participants assigned to all groups (FE, TRAD, and CF) underwent a test battery comprised of multiple measures of fitness. These measures were distributed over 3 days (with a maximum of 48 hours between testing sessions) and were completed both at the beginning and end of the study. The tests were arranged such that assessments which targeted primarily upper body muscles were alternated with those that target primarily lower body muscles, and a 3-5 minute rest period was allowed between each assessment. These methods minimized the effect of participant fatigue (resulting from the maximal effort requirements of each test) interfering with participant effort during subsequent measures, and are similar to those used to assess fitness, physiology, and performance in previous studies (Hermans et al., 2017; Stankovic et al., 2014).

Prior to initiation of any test battery, participants observed 5 minutes of seated rest, during which a member of the research team measured resting heart rate (HR) and blood pressure (BP) values – if these values were in excess of 99 beats per minute or 144/94 mmHg (for HR and BP, respectfully), another 5 minutes of seated rest occurred; this process was repeated until heart rate and blood pressure fell below the aforementioned cut-offs. All testing occurred during within 7 days of the first training session, and then again at the end of the study (within 7 days of the last training session). No more than 48 hours separated testing sessions during both pre- and post-intervention periods. The individual protocols for each test are outlined in the following section. A full schedule reflecting the training and testing study timeline for each group can be found in Appendix M (figure 4); the order of assessments to be completed during testing days 1, 2, and 3 can be found in Appendix M (figure 5).

Aerobic fitness

The 20m shuttle run test was chosen to assess the aerobic power of participants in the current study; strong correlations between predicted shuttle run VO2max compared to treadmill VO_{2max} have been found (Ahmaidi, Collomp, Caillaud, & Prefaut, 1992; Léger & Lambert, 1982; Léger & Gadoury, 1989; Stickland, Petersen, & Bouffard, 2003). This body of literature agrees with the work of Mayorga-Vega (2015), who confirmed (via meta-analysis) that the shuttle run test provides a moderate-to-high mean correlation coefficient of criterion-related validity for estimating VO_{2max}, especially in adult populations (r=0.92).

The original protocol of the shuttle run test has been previously outlined in the literature (Leger et al., 1988), and remained unchanged in the current study. Participants performed this test by running back and forth between 2 lines (separated by a distance of 20 meters) continuously, with incremental increases in running speed occurring every minute (i.e. every stage) – although an earlier version of the shuttle run test involved incremental speed increases of 0.5 km/h every 2 minutes (Léger & Lambert, 1982), this was soon modified by its creators to increase participant motivation during testing (Léger, Lambert, Goulet, Rowan, & Dinelle, 1984). Thus, all participants in the current study began the test by running at a speed of 8.5 km/h, and this speed was increased by 0.5 km/h per minute – no warm-up was permitted before test initiation, due to the relatively slow running velocity of the first stage, and the gradual increases in test difficulty (Aandstad et al., 2011). Shuttle run test scores, corresponding running speeds, and resulting estimated VO_{2max} values can be found in the Table 3.

Anaerobic Fitness

The current study assessed both upper and lower body anaerobic fitness of participants using methods derived from standardized Wingate protocols (Bar-Or, 1987) for anaerobic alactic and lactic power. Upper and lower body anaerobic fitness of participants was measured using an arm crank ergometer and bicycle ergometer (respectfully) – data from these tests were recorded using an automated computer program, connected to each ergometer.

Protocols for both measures were relatively similar (with the exception of differences in resistance). Prior to beginning either test, participants sat on a chair for 5 minutes while a member of the research team discussed the test details and protocol. At the end of this period, pre-Wingate blood lactate ([BLa-]) was be taken from the finger tip of participants, and measured according to methods utilized in previous CrossFit studies (Maté-Muñoz et al., 2017; Murawska-Cialowicz et al., 2015). In the current experiment, a "Lactate Pro" blood lactate test meter (model LT-1710, manufactured by ARKAY inc. Kyoto, Japan) was utilized in conjunction with manufacturer specified blood lactate strips. The blood lactate meter was calibrated using a test strip (according to manufacturer instructions) before starting each test battery. Following this measure, researchers assisted participants in adjusting Wingate equipment to the following specifications: the saddle height, handle bar height, pedal strap tightness, and handle bar angle of the Monarch bicycle used during the lower body test was adjusted according to participant preferences (Jaafar et al., 2014); the height of the arm crank ergometer and distance from the associated chair (on which the participant was sitting during the upper body test) was positioned such that the center of rotation of the crank was level with the participant shoulders, and the participant exhibited near full arm extension while pedaling (Forbes, Kennedy, Boule, & Bell, 2014). In both cases, these adjustments were recorded during the pre-intervention testing, such that individualized equipment settings could be replicated during the post-intervention tests.

Following equipment set up, participants then performed a 5-minute warm-up, comprised of light intensity pedaling/cranking punctuated with 6-second maximal intensity sprints during the 2nd and 4th minutes (Jaafar et al., 2014). Both the lower and upper body Wingate warmup was performed while pedaling at a pace of 60-70 RPM (with no added resistance) (Mermier, Janot, Parker, & Swan, 2000). During the warm-up, researchers reminded participants to remain in the fully seated position (which had to be maintained during both tests, as postural changes have been previously shown to affect Wingate results (McLester, Green, & Chouinand, 2004). 1-2 minutes of seated rest followed the warm-up in both tests, in order to allow researchers to set the individual load for each participant. To initiate either test, participants began pedaling/cranking for 1 minute at a light intensity (identical to the load/RPM utilized during the warm-up). During the last 10 seconds of this minute, a researcher verbally prompted the participant to begin accelerating to a maximal pedal/crank velocity. Participants then accelerated to a maximum pedaling speed during the last 3 seconds of the minute (indicated by a verbal count down from 3 to 0), after which the maximum resistance (i.e. the test workload intensity) was set (Forbes et al., 2014).

Workload intensity for the lower body test was set at 0.092 kg/kg bodyweight and 0.075 kg/kg bodyweight for male and female participants (respectfully) (Mermier et al., 2000); intensities for the upper body test were based on the work of previous authors (Forbes et al., 2014), and set at 0.075 kg/kg bodyweight and 0.065 kg/kg bodyweight for male and female participants (respectfully). After the maximum resistance was set, participants pedaled as fast as physically possible for 30 seconds in duration. A 5-minute cooldown (of pedaling/cranking slowly, with no added resistance) followed test termination; participant blood lactate was measured 3 minutes (while recovering) and 7 minutes (while seated) after the test was completed, in order to evaluate any change in energy system contribution resulting from the CF and TRAD training protocols. The computer connected to the ergometer recorded values of power output every 5 seconds; peak 5 second output (relative to participant body weight), average power output over 30 seconds (relative to participant body weight), were subsequently calculated for both upper and lower body Wingate trials.

Musculoskeletal Strength

The musculoskeletal strength of participants was measured via a series of test designed to reflect body part specific adaptations to resistance training. All of these utilized a standardized multiple-repetition maximum (MRM) protocol for athletic populations (Darrall-Jones, Jones, & Till, 2015). Participants were asked to gradually progress loading in each exercise across 4 sets – the first set was comprised of 8 repetitions completed at a participant selected “easy” load; 1 minute of rest followed this set. During the second and third sets, participants performed 5 repetitions at self-selected “moderate” and “difficult” loads; one minute of rest followed both of these sets as well. At the onset of the fourth set, participants were asked to complete 3 repetitions at a load that they deemed would lead to technical failure (see below for exercise specific descriptions of failure). Participants had 3 attempts to achieve this load – loads were increased by 2.5 lb increments (or higher), and 3 minutes of rest followed each 3 repetition maximum (RM) attempt (Weakley et al., 2017) In order to compare MRM results across multiple testing sessions, the results of each test were equated to an estimated 1-RM value, according to load conversion charts previously established by the NSCA (Baechle & Earle, 2008).

Upper Body Pull Strength

The pronated pull-up 1-RM or assisted pull-up 1-RM protocols were used to measure upper body pull strength of participants. This test has been previously used in the literature to assess upper body strength (Barfield et al., 2012; de Sousa et al., 2016; Sobrero et al., 2014), and confirmed as a valid means of evaluating upper body, arm, and shoulder girdle fitness (Baumgartner, 2007; Pate, Burgess, Woods, Ross, & Baumgartner, 1993). A high degree of reliability in the 1-RM pull-up test has also been established by multiple authors (Parikh & Arora, 2014; Weakley et al., 2017). Specific test procedures and test termination determinants (i.e. technical failure) followed the methods utilized by previous authors (Barfield et al., 2012) – the starting position of this test (and each repetition) involved participants free-hanging from a straight, fixed pull-up bar, with hands pronated and separated by a distance equivalent to shoulder width; the lower body was not allowed to be supported in anyway. In instances where participants could not perform a single pull-up, an assisted pull-up machine was used – use of this machine involved adding counterweight to a participant's body weight via knee support. Successful completion of a repetition involved participants puling themselves vertically, such that their chin rose above the bar – no kipping, swinging, jumping, kicking, or other additional momentum to increase vertical displacement was permitted. This test was terminated when the participant reached technical failure, indicated by the inability to perform a full range of motion pull-up (with the chin passing above the bar), and/or the additional use of momentum (i.e. "kipping"). Repetitions initiated without the arms fully extended (in the bottom position) were not counted. This test was scored according to the maximum number of technically correct pull-ups performed by each participant; bodyweight, or bodyweight + added weight (via rubber weight plates, suspended from the participants' waist) was used to calculate estimated 1-RM values for the standard pull-up protocol; bodyweight minus counterweight (provided by the assisted pull-up machine) was to calculate estimated 1-RM values for the assisted pull-up protocol.

Upper Body Push Strength

The barbell bench press 1-RM test has been used to assess upper body strength in previous CrossFit studies (Drake et al., 2017; Sobrero et al., 2014) and confirmed as a reliable method to of measuring this variable in a variety of different populations (Dong-il Seo et al., 2012; Parikh & Arora, 2014; Weakley et al., 2017). Technical failure in this test was defined as an inability to maintain an unassisted, full range of motion over the course of a single repetition – full range of motion required the barbell to touch the participants' chest (at the bottom position of the movement) and full extension of participants' arms (at the top position of the movement). Prior to beginning each set, participants were positioned supine on a bench, such that their eyes were located directly under the barbell, their hands were placed on the bar (such that 90 degrees of elbow flexion was achieved), and their feet, back, shoulders, and head were firmly planted on the floor/bench. Spotters were present during all sets of the barbell bench press test – any instances in which the spotter intervened to assist the participant in lifting the barbell back onto the rack were deemed to be indicative of technical failure.

Lower Body General Strength

The barbell back squat has also been used to assess musculoskeletal strength in multiple training articles (Butcher et al., 2015; Drake et al., 2017; McKenzie, 2015; Paine et al., 2010). The reliability of both the 1-RM and 3-RM version of this test have been previously validated by studies in the sport science literature (Comfort & Mcmahon, 2015; Parikh & Arora, 2014). Proper technique in this test was defined as performance of the squat exercise with legs bent at 90 degrees (i.e. parallel to the floor) or lower in bottom position of the movement, and legs and hips fully extended in the top position of the movement. A box or medicine ball was used as a target for participants unable to reach at least 90 degrees of knee flexion during sets with easy intensity loads – participants using this equipment were instructed to carefully touch the box/medicine ball with their buttocks, without placing any significant body weight on the apparatus (i.e. without sitting on the equipment). Sitting on the equipment (and any associated momentum required to accelerate out of the sitting position) was indicative of incorrect squat form, and resulted in test termination.

Lower Body Isolated Flexion and Extension Strength

The current study evaluated both lower body isolated flexion and extension strength using Life Fitness selectrised machines. The reliability of these exercises in assessing lower body

1-RM strength has been confirmed by previous research (Dong-il Seo et al., 2012; Parikh & Arora, 2014).

Prior to both tests, participants were positioned on either the seated leg extension or prone leg curl machines (for leg extension and leg flexion tests, respectfully) according to the manufacturer instructions located on placards of both machines. Researchers ensured that participants' knees rotated about the correct pivot point, and that the body was secured (such that no movement of the hips or upper body were present while performing leg extension/flexion). Termination criteria for both tests were defined as the inability to maintain full, unassisted range of motion during a repetition – during leg extension exercise, the end range of motion was defined as participants' lower legs being fully extended about the knee (and parallel to the ground); the end range of motion for the leg flexion exercise was defined as the mobile leg pad touching the participants buttocks. The starting point of each repetition required the mobile weight plates of each machine to be in contact with the weight stack (which remained immobile) during the exercise. An inability to reach these start/end range of motions and/or any visual movement of the hips or upper body was considered technical failure, and resulted in test termination.

Musculoskeletal Endurance

To date, the current CrossFit training literature is lacking in evaluations of muscular endurance – only 5 studies within this field have performed measures of muscular endurance; of these, 3 have utilized maximal repetition push-ups (Eather et al., 2016; Paine et al., 2010; Sobrero et al., 2014), 2 have used maximal repetition pull-ups (Barfield et al., 2012; Sobrero et al., 2014), curl-ups (Eather et al., 2016; Paine et al., 2010), and/or field cardiovascular tests (2 km row or 2 mile run as fast as possible) (Kramer et al., 2016; Paine et al., 2010), and only one has utilized an exercise (YMCA – bench press) that does not use body weight as the primary load (Barfield et al., 2012). In the interest of providing more rigorous data beyond these primarily field-based measures, the following protocols have been adopted to evaluate muscular endurance of participants in the current study.

Upper Body Pull Endurance

Although the bent-arm hang test has not been previously utilized to measure muscular endurance in CrossFit training studies, it has been used in prior sports science research as a measure of sport specific muscular endurance in the shoulder girdle and associated upper body musculature (Baláš, Pecha, Martin, & Cochrane, 2012; Espana-Romero et al., 2009; Grant, Hynes, Whittaker, & Aitchison, 1996; Hermans et al., 2017; Wall, Starek, Fleck, & Byrnes, 2004; Watts, Martin, & Durtschi, 1993). This test was chosen over the maximal repetition pull-up test in the current study, due to the fact that multiple participants were not able to complete a single pull-up. Additionally, the use of a bent-arm hang test prevented significantly stronger participants from performing multiple minutes of pull-ups; this improved testing efficiency for the researchers, and reduced upper body fatigue from interfering with subsequent fitness tests. As in previous studies, time to absolute failure (i.e. inability to keep one's chin suspended above the pull-up bar) was the recorded metric for this physiological variable in the current experiment.

Specific testing methods similar to those utilized by previous researchers (Hermans et al., 2017) were used for bent arm hang protocols; participants performed the bent arm hang test on a standard pull-up bar (located in the Hanson Fitness and Lifestyle Center). Using a step (if necessary), participants grabbed the bar with hands in a pronated position (palms facing away from the body), separated by a shoulder width distance. Jumping to reach the bar was not permitted (in order to prevent swinging/displacement of the body out of a vertical position). All fingers (including thumbs) were allowed to contact the bar and bear load in the current test. Participants were asked to gently lift themselves into a vertical hanging position in which their chin was located above the pull-up bar, and their arms were bent (at <90 degrees). A member of the research team started the test time when both feet of the participant left the ground or box. The test was terminated when participants were unable to maintain the hanging position (as indicated by their chin dropping below the top of the pull-up bar). Participants had 2 attempts to complete the test; each attempt was separated by a 90 second recovery period. The maximal time to fatigue between the 2 trials was recorded and used for subsequent analyses. No exercise specific warm-up was allowed before initiating the bent-arm hang test.

Upper Body Push, Lower Body Flexion, and Lower Body Extension Endurance

All 3 of these tests followed a methodology similar to the aforementioned protocols used to assess muscular strength (using the same exercises) – the tests were also terminated upon technical failure (as defined in the above section on muscular strength tests). A resistance of 50% of baseline 1-RM bench press, prone leg curl, and seated leg extension strength (of each individual participant) was used as the load for the upper body push, lower body flexion, and lower body extension endurance tests (respectively), and all repetitions were performed at a rate (monitored via metronome) of 30 repetitions/minute (i.e. 60 beats per minute, with 1 beat for the "up" movement, and 1 beat for the "down" movement in each repetition). This protocol was based on a combination of previous research (i.e. YMCA bench press test to failure (Barfield et al., 2012)) and unpublished pilot testing (Mcweeny, 2013), which previously confirmed the efficacy of these test parameters in efficiently measuring muscular endurance within a greater fitness test battery for trained adults. The 50% 1-RM bench press test was chosen (instead of the maximum repetition push-up test) in order to provide a more suitable measure of muscular endurance for the population of the current study – push-up tests previously described in the CrossFit literature were performed by studies examining the impact of CrossFit training on children (15-16 years old) (Eather et al., 2016), middle aged (30-45) officers in the US armed forces (Paine et al., 2010), or recreationally active young adult females only (Sobrero et al., 2014). Because participants in the current study were predominantly sampled from a university fitness center, it was suspected that they would be more accustomed to the bench press exercise than participants in the previous studies (which utilized the push-up to failure endurance test). Thus, the 50% 1-RM bench press test was selected to measure upper body muscular endurance as a means of improving test efficiency, as well as reducing the chance of participant fatigue (following the performance of multiple minutes of pushups) from interfering with subsequent fitness tests.

General Lower Body Endurance

A single test was chosen to assess general lower body muscular endurance. The maximum repetition bodyweight squat test consists of completing as many bodyweight squats as possible (i.e. without an external load) in 60 seconds – in order for a repetition to be counted, participants had to contact a 9kg medicine ball with their buttocks (at the lowest point of the movement), then fully extend their legs and hips (at the highest point of the movement). This test has been previously used to evaluate lower body endurance in a CrossFit training study (Barfield et al., 2012) as well as in applied settings (Baumgartner, 2007) - combined with previously unpublished literature (Mcweeny, 2013), and the fact that limited measures of lower body muscular endurance have been performed in previous CrossFit training studies to date, the maximum repetition bodyweight squat test was chosen because of its efficient nature; compared to a 50% 1-RM barbell back squat test (that can last minutes on end, especially in participants with high levels of lower body fitness), the short duration of this measure was deemed to be significantly less likely to interfere with subsequent measures within the greater test battery, while still providing an evaluation of lower body muscular endurance.

Instantaneous Power

Lower Body Instantaneous Power

The countermovement jump has been used in various CrossFit studies (de Sousa et al., 2016; Maté-Muñoz et al., 2017; Sobrero et al., 2014) as a measure of explosive lower limb power, and was therefore chosen to assess lower body instantaneous power in the current study. As per the protocol outlined by Patterson and Peterson (2004), participants' maximum standing reach height was measured via extending the dominant arm strait up (while keeping both feet together, planted flatly on the ground), and touching the maximum possible height on a vertical tape measure. Following one practice jump, participants performed a counter movement jump (whereby participants were told to lower themselves to a 90 degree squat position, extend their arms backwards behind their torso, then explosively jump and swing their arms forward, attempting to reach the highest possible marker on the Vertec apparatus with their dominant arm). No additional momentum or extra steps were permitted during the tests - participants were required to start and finish each jumping trial from a 2-footed stance. Members of the research team monitored participants for proper jump form - jump heights achieved using incorrect technique were not counted. Two jump attempts (with one minute rest between attempts) were allowed - the maximum distance between standing reach height and jump height was recorded.

Upper Body Instantaneous Power

A horizontal medicine ball toss from a seated position was used to assess the instantaneous upper body power of participants. A similar version of this test has been previously used as a measure of upper body power by authors in the CrossFit community (Sobrero et al., 2014) as well as studies assessing the power capabilities of overhead athletes (Borms, Maenhout, & Cools, 2016). Prior to testing, participants were instructed to sit on the ground, with their legs fully extended, and their back, shoulders, and head against a perpendicular wall. Holding an 8 lb medicine ball against their chest (with elbows fully flexed, and shoulders abducted to 90 degrees, or parallel to the floor), participants were then asked to press the medicine ball horizontally, as hard as possible, in an attempt to toss the ball away from their body to a maximum horizontal displacement on the floor. Following 2 practice attempts, each participant performed 2 throws (separated by 1 minute of rest) - the horizontal distance of each throw was determined via visual inspection of the landing spot of the medicine ball on the floor, and measured using an adjacent tape measure. The distance of the best throw was used as a measure of instantaneous upper body power. Throwing form was monitored by members of the research team - throws performed with incorrect technique (i.e. back, shoulders, or head leaving the wall upon throwing; initially holding ball in a way that it does not contact the chest; starting with elbows not fully flexed, or shoulders not abducted to 90 degrees) were not recorded. A similar protocol has been previously used to assess upper body power in the literature (Borms et al., 2016).

Statistical Methods

Primary analysis: The one-way ANCOVA statistical test (with baseline test-values as the covariate, training modality as the independent variable, and post-training test-values as the dependent variable) was used to analyze differences in post-training means in muscular strength, muscular power, muscular endurance, energy metabolism, and aerobic power outcomes between all study groups in the current experiment (while simultaneously controlling for differences in fitness between groups at baseline).When significance was detected, a Post-Hoc LSD test was used to discover the location of the significance (i.e. which two groups had significantly different post-training means) in the measured variable.

Secondary analysis: Paired-samples T-tests were used to determine the pre-post change (i.e. baseline vs. post-training means) within every study group, for each of the aforementioned fitness outcomes.

In all tests, the significance value was sets at $p < 0.05$; IBM® SPSS (Statistics Standard GradPack 23 for Windows) was the program used to perform all statistical tests in the current study.

Additional Calculations

All study participants were asked to record their subjective session-based rating of perceived exertion (RPE) (based on the Borg CR-10 scale) following each training session (see Appendix L). This scale ranges from 0-10, where 0 indicates an exercise intensity equivalent to rest (i.e. no effort), and 10 indicates an intensity equivalent to maximal effort. Then, each reported exercise session was given an intensity rating (i.e. light, moderate, or vigorous intensity exercise) based on standards provided by CSEP (light effort = RPE of 0-3; moderate effort = 4-6; vigorous effort = 7-10). Summation of the total number of exercise minutes accumulated for each intensity category was subsequently performed for each group; the results of these calculations can be seen in Appendix A (Table A2).

Chapter 4: Results

Descriptive Data

Descriptive information of study participants can be found in Tables A1 and A2. CF, TRAD, and FE were comprised of participants with an average age of 21 – 25 years and each group had an even number (n=5) of males and females. There were no significant differences between the average exercise frequency and history of each group prior to initiating training; however, participants in both TRAD and CF reported performing more CrossFit workouts prior to study initiation than their counterparts in FE (see Table A1). Similarly, both CF and TRAD participants attended approximately the same number of supervised training sessions (15 and 16, respectively), while participants in FE did not attend any supervised sessions over the course of the study. However, the duration between the first pre-training testing session (i.e. first day of the study) and the last post-training testing session (i.e. the last day of the study) was either 49 or 50 days in all three study groups (see Table A2).

There were no significant changes in bodyweight across time for CF (t(9) = 0.99, p = .346), TRAD (t(9) = - 0.06, p = .090), or FE (t(9) = 0.21, p = .836) (see Tables A1 and A2). Additionally, no between group differences in post-training bodyweight were detected (F(2,29) = 0.52, p = .601). The three groups also did not differ significantly in total exercise time accumulated over the duration of the study (F(2,29) = 0.85, p= .440), or time spent performing moderate (F(2,29) = 0.73, p = .489) or vigorous (F(2,29) = 0.76, p = .478) exercise (see Table A2).

Energy Metabolism

Primary analysis: Post-hoc analysis revealed that CF had a lower post-training resting blood lactate (-1.5 mmol/L) relative to FE (p = 0.015, 95% CI [-2.62, 031]) (see figure 3B).

Secondary analysis: CF did not incur a significant increase (or decrease) in any blood lactate measure over time. Detailed energy metabolism data collected in the current experiment are displayed in Appendix C.

Anaerobic Fitness

Change in instantaneous upper body anaerobic power was measured via the medicine ball toss test (see figures 1A and 1C).

Primary analysis: the post-training medicine ball toss distance of CF did not differ from either FE or TRAD during the study (see Appendix D).

Secondary analysis: CF did not experience a significant change in med ball toss distance over time.

Mean and peak upper body anaerobic power was measured using an arm crank ergometer Wingate test protocol.

Primary analysis: the post-training upper body mean and peak power outputs of CF were not different from the other two study groups (see Appendix D).

Secondary analysis: CF did not incur a significantly different post-training mean or peak upper body power output relative to baseline (see figure 1A).

Lower body peak and mean anaerobic power was measured via a cycle ergometer Wingate test protocol; lower body instantaneous power was measured using the vertical jump test.

Primary analysis: post-training lower body peak power output and vertical jump height were not found to be different between the study groups (see Appendix D). Between group differences for anaerobic fitness were, however, detected in the post-training mean power output of the lower body Wingate test (F(2,29) = 5.27, p = .012). Post-hoc analysis revealed that the post-training lower body mean power output of CF was 66.71 watts less than TRAD (p = .025, CI 95% [-124.45, -8.97]) and 96.36 watts less than FE (p = .004, 95% CI [160.05, -32.68]); these comparisons are illustrated in Figure 1B.

Secondary analysis: CF did not incur a significant change in post-training vertical jump height relative to baseline. However, CF did experience a decrease in mean lower body power output by -73.43 ± 22.84 watts (t(9) = -3.22, p = .011) over the duration of the study (see figure 1A).

Aerobic Fitness

Primary analysis: As displayed in Appendix E, no between group differences were detected in either of the post-training aerobic fitness measures.

Secondary analysis: Positive changes between baseline and post-training maximum shuttle run stages (t(9) = 3.90, p = .004, 95% CI [0.36, 1.34] and estimated VO_{2max} (t(9) = 2.69, p = .025, 95% CI [0.33, 3.87]) were found in the CF group (see figure 3C). Specifically, this group experienced a 0.85 ± 0.22 and 2.10 ± 0.78 ml/kg/min increase in maximum shuttle run stage and estimated VO_{2max} over time (respectively).

Musculoskeletal Strength

Primary analysis: No between group differences were found for post-training estimated 1RM of any strength measure (see Appendix F).

Secondary analysis: CF exhibited increases in barbell bench press, leg extension, pull-up, and leg curl estimated 1-RMs overtime (see figure 2D).

Musculoskeletal Endurance

Primary analysis: As shown in Appendix G, no between group differences were detected in the post-training maximum number of bodyweight squats.

Differences between post-training bent-arm hang time existed between the three study groups (F(2,29) = 3.56, p = .043) (see figure 2B). Specifically, post-hoc analysis revealed that the post-training bent-arm hang time of CF was 4.63 seconds longer than TRAD (p = .026, 95% CI [0.61, 8.64]). Greater details of bent-arm hang time data analysis are presented in Appendix G.

No between group differences were detected in post-training hamstring muscular endurance (measured via leg curl repetitions to fatigue) (see Appendix G).

Differences were, however, detected between the leg extension endurance of the study groups (F(2,29) = 4.98, p = .015). Specifically, post-training leg extension endurance was found to be greater (by 5.96 reps) in CF than FE (p = .009, 95% CI [1.65, 10.28]) (see figure 2C).

Secondary analysis: CF exhibited increases in the maximum number of bodyweight squats performed in 1 minute from pre- to post-training (see figure 2A).

Positive changes over time were found in the bent-arm hang times of CF; specifically, CF improved their post-training hang time to failure by 3.63 ± 0.89 seconds (t(9) = 4.10, p = .003, 95% CI [1.63, 5.64]) relative to baseline.

Leg extension endurance between baseline and post-training (see figure 2A) was not different post training in CF.

Chapter 5: Discussion

CrossFit advertises itself as an “empirically driven [and] clinically tested” (Glassman, 2010) modality of resistance training, despite a paucity of peer-reviewed academic literature examining the prolonged effects of CrossFit training on different attributes of fitness, as well as the relative effect of CrossFit vs. traditional modes of resistance training on these attributes. Only 3 studies published to date (Barfield et al., 2012; de Sousa et al., 2016; Jeffery, 2012) have, to this author’s knowledge, compared CrossFit to traditional resistance training modalities to date. Given this lack of research, and the major differences between the protocols used in these studies, comparisons of results are difficult to make. Further empirical research is therefore needed to validate the aforementioned claims proposed by CrossFit Inc. (in the CFTG), especially considering the global success and growing popularity of CrossFit as an alternative to traditional modality resistance training. Thus, a controlled training study was completed to better identify the specific fitness adaptations following exclusive use of either traditional or CrossFit resistance training workouts for 6 weeks.

The secondary analyses revealed significant improvements in fitness for the CF group following 6 weeks of training; however, not all fitness outcomes increased from pre-to-post training in CF and TRAD, and some actually decreased overtime, implicating that other training factors that may have actually caused regressions in fitness. The reasons for this decrease include a) non-functional over-reaching of CF participants (which was observed in the form of stagnation and regression in certain fitness attributes relative to baseline) and/or b) the novel resistance training program completed by this group not providing sufficient specific overload to induce adaptation compared to pre-study training regimens; these speculations are discussed in greater detail in the following paragraphs.

Regardless of the direction of change, the principle of training specificity suggests that the fitness adaptations observed following manipulation of resistance training were specific to the type, duration, and intensity of exercise performed by participants in this study (Coffey & Hawley, 2007; McCafferty & Horvath, 1977; Reilly et al., 2009). For example, isolated knee flexion endurance (measured via prone leg curl repetitions to failure at 50% estimated 1-RM) was found to be only significantly increased in TRAD (see figure 2A); as TRAD was the only group prescribed isolated leg flexion exercise, specificity was likely at play in this fitness change.

Traditional resistance training has also been shown to influence metabolism, power, and capacity in previously published studies; increases in muscular strength of 2-20% and improvements in both lower and upper body power (when training loads range from 30-60% squat 1-RM and 46-63% bench press 1-RM, respectively) have been widely reported as a consequence of traditional resistance training interventions, in individuals with a variable training experience (Baker, Nance, & Moore, 2001a; Baker, Nance, & Moore, 2001b; Ratamess, Faigenbaum, Mangine, Hoffman, & Kang, 2007; G. Wilson, Newton, Murphy, & Humphries, 1993). Improvements in muscular endurance have also been reported following traditional resistance training (via adaptations in mitochondrial and capillary density, intramuscular enzymatic activity, and/or buffering capacity) (Koenig et al., 2001; Kraemer & Gotshalk, 2000).

Although the aforementioned effects of traditional resistance training have been heavily researched and incorporated into major publications of widely recognized strength and conditioning organizations (e.g. ACSM and NSCA) (Jeffery, 2012), considerably less work examining the effects of CrossFit modality training has been performed to date. Consequently, authors empirically investigating the impact of CrossFit on fitness often report conflicting results; this may be due to the extremely variable nature of CrossFit training programs and research designs utilized in the currently limited body of CrossFit literature (Drake et al., 2017).

Additionally, the CrossFit literature has mixed study timelines, with certain authors reporting no changes to fitness based outcomes after 4 weeks of CrossFit training at a frequency of 5 workouts per week (Drake et al., 2017), despite others finding significant improvements in fitness measures following 10 weeks of CrossFit style training (Paine et al., 2010; Smith et al., 2013). In the current study, significant improvements in fitness of the CF group were observed in as little as 18 training sessions (distributed over a 6 week period). Collectively, these studies suggest that at least 6 weeks of CrossFit training (at a maximum frequency of 4 workouts per week) can elicit significant changes in fitness, with the possibility of longer training durations potentially producing further improvements.

As such, the majority of empirical research on CrossFit modality training to date is by no means definitive, but suggests that sustained periods (4-10 weeks) of performing CrossFit WODs can lead to improvements in VO_{2max} overtime (Bellar et al., 2015; de Sousa et al., 2016; Gerhart, 2014; Murawska-Cialowicz et al., 2015; Smith et al., 2013); however, these findings are contradicted by other recent studies (Drake et al., 2017; Outlaw et al., 2014).

Interestingly, studies investigating the effects of CrossFit training on power output show conflicting results as well; while some authors have demonstrated that CrossFit training can elicit significantly greater improvements in power output (measured via the Margaria Kalamen test) relative to training consistent with the ACSM guidelines for resistance training (Jeffery, 2012), others have reported that individuals trained using the ACSM guidelines experience a significantly greater improvement in power output (measured via standing long jump), relative to individuals trained using CrossFit guidelines presented in the CFTG (Barfield et al., 2012).

With regards to changes in muscular strength and endurance, only one study to date has compared the effects of controlled CrossFit vs traditional resistance training interventions on these attributes. Barfield et al. (2012) reported no differences in strength (measured via hand grip dynamometer) between recreationally active university students who completed either CrossFit or traditional resistance training workouts for 10 weeks (at a maximum frequency of 2 workouts per week). Similarly, these authors did not report any differences between traditional and CrossFit trained groups with respect to performances on maximum pull-up repetition and YMCA bench press tests for muscular endurance. While another recent study demonstrated average increases in shoulder press 1-RM, back squat 1-RM, and deadlift 1-RM strength of 9.42%, 13.41%, and 21.11% (respectively) in individuals who completed 6 weeks (at a minimum frequency of 4 workouts/week) of CrossFit training, these results may be limited by the low number of participants in the study (n=14), as well as the absence of a control group (Paine et al., 2010). Interestingly, the muscular endurance of participants in the same study (measured via maximum pushup and sit-up repetitions in 2 minutes) also improved, on average, by 7.33% and 4.77%, respectively); however, these findings are also limited by the aforementioned study design issues.

Although the physiological mechanisms behind observed changes in fitness following CrossFit training have yet to be confirmed or researched at any great depth, it is probable that training specificity had a role to play in the metabolic adaptations seen in this study (Coffey & Hawley, 2017; McCafferty & Horvath, 1977; Reilly et al., 2009). The following sections will therefore highlight the changes in components of fitness that were novel to the study, then attempt to combine training theory and cellular exercise physiology research into some unifying hypotheses and, finally, provide some practical recommendations regarding the utility of CrossFit for healthy adults and athletes.

Novel Changes in Measured Fitness Components

One major finding of the primary analyses was that lower body anaerobic mean power output (measured via 30 second cycle Wingate test) was significantly lower in CF than both TRAD and FE following training (see figure 1B). This finding directly contradicts the primary hypothesis regarding the expected superiority of CrossFit to elicit significantly greater improvements in anaerobic power relative to both the traditional and free exercise training interventions utilized in the current study.

Other exercise physiology literature has shown that training which is not specific to the duration and intensity of a certain pathway can lead to stagnation or even regression in previous training induced adaptations of this pathway (Isratel et al., 2016). Thus, it seems likely that a significantly lower post-training mean low body anaerobic power was observed in CF (relative to TRAD and FE), because the CrossFit WODs performed by this group typically included durations and intensities of exercise that typically result in the energy for muscular contractions being predominantly produced through aerobic metabolic pathways (Coffey & Hawley, 2007).

CrossFit workouts in the current study (in line with the programming recommendations of the CFTG) did not prescribe any rest periods within WODs; additionally, because WODs encouraged participants to complete as many rounds of a circuit (i.e. 3+ exercises, performed back to back with no rest in between) in 12-20 minutes as possible, or complete circuits (lasting longer than 3 minutes) "for time" (i.e. as fast as possible), or perform a single metabolically demanding exercise (e.g. running, rowing on a row ergometer, or skiing on a ski ergometer) for >20 minutes, it may be that performance of CrossFit workouts acutely exposed CF participants to training stimuli that would have predominantly stressed the aerobic energy system. Performance of these CrossFit workouts over 6 weeks may have therefore produced a chronic training stimulus that targeted the aerobic energy production pathways more than anaerobic pathways, thereby reducing adaptations from occurring within the anaerobic physiology of CF participants.

In line with the primary purpose, comparisons of the CrossFit and traditional workout programs used by participants in the current study support the premise that traditional workouts would have emphasized a greater proportion of energy production from the anaerobic systems. Because rest periods were observed between each set of exercises performed in traditional workouts, it is rare that participants in TRAD sustained bouts of exercise for more than 3 minutes before resting. As FE likely trained in a similar manner to TRAD, this may explain why CF exhibited a significantly lower mean post-training lower body anaerobic power output relative to both TRAD and FE.

Other studies have reported improvements in the anaerobic power of participants (following sustained CrossFit training) using alternative methods of measurement (i.e. the maximal accumulated oxygen deficit (MAOD) protocol, an anaerobic treadmill test (specific protocols not discussed), and the Margaria-Kalamen Power Test) (Drake et al., 2017; Goins et al., 2014; Jeffery, 2012) (respectively). Although these different methods do not allow direct comparison of the results of the current study to others, the finding that anaerobic fitness decreased in the current study is unique; additionally, the Wingate is considered a gold standard test of anaerobic fitness in the exercise physiology domain (Aziz & Chuan, 2004; Bar-Or, 1987; Ramírez-Vélez et al., 2016), with other authors demonstrating that anaerobic phosphagen and glycolytic metabolism provides the majority of energy (31.1% and 50.3%, respectively) for exercise during a standard Wingate test (Beneke, Pollmann, Bleif, Leithäuser, & Hütler, 2002). In other words, the lower body Wingate test demonstrates the ability of the immediate (i.e. ATP/CP), and short term (anaerobic-glycolytic) metabolic systems to produce ATP for muscular work during maximal intensity exercise. Thus, use of the Wingate protocol to evaluate change in anaerobic fitness is valid - decreases in lower body anaerobic power (measured via the Wingate test) was found in 9/10 CF participants (see Table 4).

Another finding which speaks to the primary purpose and supports the specificity factors associated with resistance training includes the increased upper body pull endurance of CF (see figure 2A). The greater post-training mean upper body endurance of CF compared to TRAD (figure 2B) was expected (based on the primary hypothesis of this study), and can likely be attributed to differences between TRAD and CF in exercise type, intensity, and/or duration.

Specifically, when compared to TRAD participants, CF performed different durations, intensities, and types of upper body pulling exercises (see appendices I and H, respectively for specific workouts completed). Although no other CrossFit studies to date have tested upper body muscular endurance using the bent-arm dead hang method, one has examined the effect of CrossFit training on pull-up endurance (i.e. maximum number of pull-ups performed in 1 minute), with results that contradict those of the current study. Barfeild et al. (2012) found that performing either CrossFit or traditional modality resistance training workouts (delivered in in the format of a “Basic Instruction Program” class) improved performance in the maximum repetition pull-up test, with no differences in this measure between CrossFit and traditionally trained groups. In the current study, the use of a bent-arm hang test (to muscular failure) was chosen over the pull-up test, due to the expected (and observed) inability of many participants to perform a single bodyweight pull-up through a full range of motion, without any additional vertical momentum from jumping or kipping.

According to the secondary analysis of upper body pull endurance data, TRAD did not improve bent-arm hang time in the current study; although both the TRAD and CF groups were prescribed different exercises that targeted the same muscles, the muscle action of these exercises was not the same. For example, TRAD was prescribed the cable latissimus dorsi pulldown and cable seated row exercises to target the muscles of the back; these were more isolative than the back exercises performed by CF (i.e. pull-up or assisted pull-up), as both the pulldown and row exercises involved positioning oneself in a sitting position (in which the lower body was stabilized via roller pads and a horizontal seat), while the pull-up required suspension of one's entire bodyweight on the shoulder girdle musculature (with no stabilization of the lower body).

While there are no studies to date (to this author's knowledge) comparing the activity of the shoulder girdle musculature during non-stabilized pull-up vs. stabilized seated pull-down exercises, a recent undergraduate thesis in exercise science (Löfquist, 2017) demonstrated that the only significant difference in muscle activation during a suspended chin-up and seated latissimus dorsi pull-down exercises (when performed at 100% bodyweight) exercises occurred in the biceps bracii (BB) and rectus abdominis muscles (RA), with BB exhibiting more activation during the seated pull-down exercise, and the RA exhibiting greater activation during the suspended chin-up exercise. Interestingly, this study did not find any differences in the muscular activity of the latissimus dorsi (LD) and trapezius pars transversa (Tr) muscles during chin-up and pull-down exercises.

Differences in the bent-arm hang time of TRAD and CF in the current experiment may therefore be partially attributed to CF incurring greater strength increases in abdominal musculature strength than TRAD, but future research is needed to validate this speculation (as abdominal strength was not measured in the current study). Alternatively, it is possible that differences in the muscle action of upper body pulling exercises used by CF vs. TRAD are irrelevant to performance on the bent-arm hang test, because the LD muscle 1. experiences greater activation than both BB and RA during both chin-up and seated pulldown exercises, and 2. appears to be equally stimulated by both the chin-up and latissimus pull-down exercises (Löfquist, 2017).

Because both TRAD and CF performed different upper body pull exercises that probably predominantly targeted the same muscles, additional differences in training variables are likely responsible for the differences in bent-arm hang performance between these two study groups. Namely, TRAD performed stable upper body pull exercises at relatively low repetitions, using heavy loads chosen to elicit technical failure within 6-12 repetitions, while CF performed pull-ups or assisted pull-ups using only their body weight (or a fraction of their body weight if pull-ups were assisted) for sustained bouts of high repetitions (see appendices I and H, respectively). Although there is no way to confirm or deny which specific exercises were utilized by FE during the study, the fact that primary analysis of the upper body pull endurance data also revealed significant differences in the post-training bent-arm hang times of TRAD and FE (FE>TRAD; see figure 2B) suggests that FE performed pull-ups (or exercises that stressed the shoulder girdle musculature in a manner similar to pull-ups) for a duration and at an intensity different from their TRAD counterparts. Furthermore, the secondary analysis of the upper body endurance data revealed that CF and FE exhibited significant increases in upper body pull endurance while TRAD did not (see figure 2A), indicating that exercise variables such as intensity and number of repetitions/duration likely have a more important influence on performance of exercises like the bent arm hang, relative to the muscle actions used for training the associated upper body musculature.

Based on these findings and the work of others (Bamman, Petrella, Kim, Mayhew, & Cross, 2007; Karp, 2001; Scott et al., 2001), it seems plausible that CF improved upper body aerobic fitness more than TRAD due to a shift in muscle fiber type (i.e. from type 2x/fast-glycolytic to type 2a/fast-oxidative-glycolytic), especially given the fact that this shift has been observed after only 6 weeks of exercise training (Esbjörnsson, Hellsten-Westing, Balsom, Sjödin, & Jansson, 1993). As aerobic sources of carbohydrate and fat substrate metabolism provides the majority of energy required to exercise during long duration activities (McCafferty & Horvath, 1977), it is plausible that a shift in type 2 fibers towards increased utilization of energy production from the aerobic systems (i.e. type 2x/fast-glycolytic to type 2a/fast-oxidative glycolytic) would also improve the ability to sustain muscular contractions during continuous bouts of exercise, and thereby improve fatigue resistance in the shoulder girdle muscles (trained via performance of pull-up exercises in the CF group) (J. Wilson et al., 2012). This training induced shift may therefore explain, in conjunction with the previously discussed heightened frequency of pull-up exercise, why CF exhibited a significantly greater post-training mean bent-arm hang time relative to TRAD.

Thus, CrossFit should be considered as a time efficient training method for individuals who participate in sports requiring large amounts of endurance from the upper body musculature (e.g. boxing, surfing, rock climbing, or kayaking) (Kamandulis et al., 2018; Lubomirov Michailov, Morrison, Mitkov Ketenliev, & Petkova Pentcheva, 2015; Méndez-Villanueva et al., 2005; Pickett et al., 2017). This recommendation is supported by the results of the primary and secondary analyses, as well as those of previously discussed authors. Collectively, this body of research suggests that the CrossFit modality of training will positively improve time to fatigue in tasks requiring sustained, long duration contractions of the shoulder griddle musculature via shifts in upper body muscle fiber composition towards fibers with more aerobic sources of energy (i.e. 2x to 2a). Therefore, it is plausible that CrossFit training will have a positive impact on the sports requiring high levels of upper body aerobic fitness; however, future research is needed to validate the effects of CrossFit on performance in such sports.

Resting Metabolism (as Measured by Blood Lactate)

Primary analysis of the energy metabolism data revealed a significantly lower post-training mean resting blood lactate of CF (relative to FE; see figure 3B). Specifically, secondary analysis of this data showed that the value of blood lactate (measured pre-Lower Body Wingate) decreased in CF but increased in FE, from pre- to post-testing (see figure 3A).

Reductions in blood lactate following training have been hypothesized to occur due to either a decreased rate of lactate production or enhanced rate of lactate clearance (Karlsson, Nordesjö, Jorfeldt, & Saltin, 1972; McArdle, Katch, & Katch, 2010). Lactate clearance is thought to be facilitated by an increase in the rate of lactate diffusion from muscle to the blood, an increase in the rate of lactate removal from the blood (McCafferty & Horvath, 1977), or an increase in lactate metabolism (Karlsson et al., 1972) in skeletal muscles or other tissues (Essen, Pernow, Saltin, & Gollnick, 1973; Hermansen, Maehlum, Pruett, Vange, & Waldum, 1973; Jorfeldt, 1970; Rowell, 1974). A delay in the onset of blood lactate (OBLA) follows these processes, and may indicate a reduced dependency on carbohydrates as the primary source of fuel for muscular contraction (Keul et al., 1972; McArdle et al., 2010).

Therefore, it is plausible that repetitive exposure to high levels of blood lactate occurred in CF, and training induced metabolic adaptations subsequently followed in order to reduce the chance of lactate inhibited carbohydrate catabolism limiting continuous exercise at high intensities (Ahlborg et al., 1967; Bergström & Hultman, 1967); this is consistent with the work of others, who have reported elevated levels of blood lactate (i.e. >10 mmol/L) following acute performance of CrossFit WODs (Farrar et al., 2010; Fernández-Fernández et al., 2015; Kliszczewicz et al., 2014). Improvement in the "metabolic machinery" of CF therefore probably increased the rate of lactate metabolism and/or clearance, resulting in habitually lower blood lactate levels (at both rest and during exercise); this adaptation in CF was detected as a reduction in resting blood lactate over time, as well as post-training resting blood lactate values that were significantly lower in CF relative to FE during rest.

Other Findings Related to Improvements in Muscular Fitness

While strength training alone has been shown to also improve aerobic fitness (Coyle, Coggan, Hopper, & Walters, 1988; Ericson, Nisell, Arborelius, & Ekholm, 1985; Frontera, Meredith, O'Reilly, & Evans, 1990; Hakkinen et al., 2003; R. O'Hara, Schlub, Khan, & Pohlman, 2004), the secondary analysis of the 20 meter shuttle run data revealed a lack of significant improvement in the aerobic fitness of TRAD participants over time, despite improved muscle strength across all estimated 1-RM measures performed by this group (see Figures 3C and 2D, respectively).

However, because secondary analysis of the data revealed that CF did incur significant improvements in estimated VO_{2max} as well as all measures of muscular strength over time (see figures 3C and 2D, respectively), these results suggest that an additional physiological mechanism (which stresses the aerobic system) was induced through CrossFit (but not traditional) modality resistance training in the current study.

Although no studies to date have performed muscle biopsies on participants who underwent CrossFit modality training, other studies investigating concurrent strength and endurance training (performed on separate workouts, but within the same day) have detected a training induced shift in muscle fiber composition, from type 2x to type 2a via muscle biopsy technique (Burke & Edgerton, 1975; R. O'Hara et al., 2004). The improved VO_{2max} in 7/10 CF participants in the current study (see Table 4) could therefore be partially attributed to the same shift in muscle fiber composition, (i.e. from type 2x/fast-glycolytic to type 2a/fast-oxidative-glycolytic), improving oxidative metabolism in the leg muscles needed to run the shuttle test.

As previously discussed in the literature review section of this thesis, CrossFit workouts (and exercises commonly performed during CrossFit WODs) have also been shown to elicit an aerobic intensity (i.e. VO_{2max}) that meets or exceeds the minimum requirements to improve cardiorespiratory fitness (i.e. 60 - 85% VO_{2max}, according to the ACSM) (Farrar et al., 2010; Fernández-Fernández et al., 2015; Kliszczewicz et al., 2014; Pollock et al., 1998). The findings regarding improvements in aerobic fitness from the current study support the work of these authors and are consistent with a number of CrossFit studies who reported significant increases in VO_{2max} following sustained CrossFit training (Murawska-Cialowicz et al., 2015; Smith et al., 2013; Zagdsuren et al., 2015).

However, Outlaw et al. (2014), reported a decrement in VO_{2max} following 6 weeks of CrossFit training. While it appears that training experience played a role in differentiating the aerobic fitness adaptations of Outlaw et al. (2014) vs. those found in the current study, the principle of overload was predominantly responsible for the VO_{2max} values reported by Outlaw et al. (2014). This is because the study design utilized by Outlaw et al. (2014) exposed their participants to a similar training stress to what they had experienced in the past 6 months (i.e. pre-study initiation); in other words, training stress was maintained throughout the study (and relative to baseline). Comparatively, resistance training was manipulated, such that participants in CF (70% of whom had not been exposed to CrossFit modality resistance training prior to entering the study – see Table A1) were exposed to a more novel form of training than the participants in the study by Outlaw et al. (2014). It is therefore likely that both the exercises and format of CrossFit workouts in the current study differed substantially from the previous training regimens used by CF participants, as this mode of resistance training included a wealth of what were probably novel training stimuli for the CF participants. Thus, differences between the post-training fitness profile of CF participants in the current study and those in who were trained using CrossFit in the study by Outlaw et al. (2014) can likely be attributed to differences in the pre-study training experience of study participants.

Because aerobic fitness plays a critical role in predicting longevity and all-cause mortality (Lee, Artero, Sui, & Blair, 2010; Satoru et al., 2009; Stathokostas, Jacob-Johnson, Petrella, & Paterson, 2004), it is important to note that decrements in VO_{2max} following short-term CrossFit training have been reported in accordance with workout programming that followed recommendations published in the CFTG (Drake et al., 2017). Drake et al. (2017) concluded that their specific CrossFit training intervention probably over-trained the study participants, resulting in the observed decrement in VO_{2max} over time – this training adaptation has been previously cited as a symptom of OTS (Hedelin, Kentta, Wiklund, Bjerle, & Henriksson-Larsen, 2000; Uusltalo, 2001). It is, however, difficult to pinpoint the specific cause of over-training in this study, as Smith et al. (2013) utilized a similar frequency of CrossFit workouts to Drake et al. (2017) (i.e. 5 days per week, separated by 2 consecutive days of rest), but reported significant improvements in VO_{2max} following 10 weeks of training. Although participants in the study by Smith et al. (2013) were recruited from CrossFit affiliate facilities (and therefore were probably more accustomed to CrossFit training, relative to the CrossFit naïve participants in the study by Drake et al. (2017)), the participants who performed 6 weeks of CrossFit training in the current study shared similar characteristics to those in the study by Drake et al., (2017) (see Table A1), but still exhibited significant improvements in VO_{2max} over time. It is possible that the small sample size utilized by Drake et al. (2017) contributed to their obscure observation of VO_{2max} decrements following short-term CrossFit training. Thus, CrossFit as a training modality, based on the weight of these results and others, seems to be generally effective at eliciting significant improvements in the VO_{2max} of adults with various aerobic fitness levels.

However, because changes in blood plasma, intramuscular mitochondrial properties, aerobic or anaerobic enzymatic activity (or density), cardiac output/stroke volume, or anatomy of the heart following training were not specifically investigated, it is plausible that some combination of these previously discussed physiological mechanisms (in conjunction with a shift in muscle fibers of the lower body from 2x to 2a) were responsible for the observed increase in VO_{2max} following 6 weeks of CrossFit training in the current study. More research is, however, needed to validate which (if any) of these proposed physiological mechanisms are responsible for CrossFit training induced adaptations in aerobic fitness.

Additional research is also needed to establish if CrossFit provides a training stimulus for superior improvements in aerobic fitness relative to isolated endurance training (i.e. without concurrent performance of strength training). While others have reported no difference in VO_{2max} following 8 weeks of endurance only vs concurrent endurance and strength training (Sedano, Marin, Cuadrado, & Redondo, 2013), the strength and endurance training in this study was performed on different days of the week. To this author's knowledge, no study to date has compared the effects of isolated endurance training to concurrent strength and endurance training (when performed within the same session), on VO_{2max}.

However, another study comparing the effects of placing strength and endurance training bouts on the same day (i.e. resistance training immediately followed by endurance training), vs. 1 day apart (resistance training on the first day, followed by endurance training on the second), found no difference in VO_{2max} after 8 weeks of training (Tohmiya, Yoshida, Kikuchi, & Nakazato, 2015). In addition to observing no difference in VO_{2max} between same-day and 1-day apart concurrent training protocols, Tohmiya et al. (2015) also reported that musculoskeletal strength was greater following 8 weeks of segregated strength and endurance training (i.e. performed 24 hours apart), compared to a program that placed endurance training immediately after strength workouts (i.e. on the same day).

Upon further examination of the CrossFit workouts performed by CF during the current study, strength type training (i.e. exercise comprised of lifting heavy, external resistance) almost always preceded, or was combined in a circuit with endurance type exercise (i.e. predominantly aerobically driven, low resistance exercise) within the same training session (see Appendix H). Thus, findings of the current study contradict those of Tohmiya et al. (2015) with respect to the effect of strength preceded endurance training (exemplified by the CrossFit program followed by CF in the current study); the secondary analyses of strength measures reveled that CF elicited a significant improvement in strength, comparable to a group (TRAD) that was only prescribed workouts containing strength (but no endurance) type exercise. While it remains unknown if endurance and strength training performed within the same workout (as during CrossFit WODs) elicits superior improvements in VO_{2max} relative to isolated endurance training, the recent work of other authors suggests VO_{2max} will not differ significantly following multiple weeks of endurance only training vs. concurrent training (when endurance and strength training sessions are separated by at least one day (Petré, Löfving, & Psilander, 2018; Sedano et al., 2013)).

As other authors have noted the benefits of incorporating resistance training into training plans for endurance athletes (Beattie et al., 2014; Paton & Hopkins, 2004; Tanaka & Swensen, 1998), it is recommend, based on findings from the current study, that endurance athletes who are already performing endurance and strength training concurrently consider implementing CrossFit into their annual plans as a time efficient means of eliciting improvements in VO_{2max}

(similar to what they would incur through other forms of concurrent training), in addition to improvements in strength. These suggestions are in line with the work of other authors (Beattie et al., 2014; Paton & Hopkins, 2004; Tanaka & Swensen, 1998) who have noted the importance of both aerobic and anaerobic fitness components in performing optimally during long distance endurance competitions. The specific impact of such variables (and therefore CrossFit) on endurance sport performance will be discussed in greater length in subsequent sections.

Although anaerobic fitness of both the instantaneous alactic and lactic muscle power was also expected to improve in CF over time (in accordance with CrossFit's proposed effectiveness at "eliciting nearly any desired fitness result" (Glassman, 2010)), the secondary analyses of lower body power measures revealed that the vertical jump height (i.e. a surrogate of alactic anaerobic metabolism) (see figure 1C), and mean power output (i.e. a surrogate of lactate anaerobic metabolism, measured during a 30 second cycle ergometer Wingate) (see figure 1A) did not improve in CF, again contradicting the secondary hypothesis.

This points to the CrossFit training program utilized by CF having a considerable oxidative component, and supports the extended time course of work required to complete a CF workout in this study; as previously mentioned, the CFTG recommends utilizing either the 12 or 20 minute "AMRAP" or "AFAP" workout formats when performing WODs, thereby encouraging participants to perform multiple functional exercises for "as many rounds as possible" or "as fast as possible" (respectively) in a 12-20 minute period of sustained exercise (i.e. with no prescribed rest). Given that the secondary analyses of the upper and lower body power data only yielded significant increases in the vertical jump height, medicine ball toss distance, and peak lower body anaerobic power output of FE (see figures 1A and 1C), it is tempting to suggest that neither the CrossFit program (used to train CF) nor the traditional resistance training program (used to train TRAD) provided enough of a training stimulus to elicit adaptations in upper and lower body anaerobic power. However, this conclusion seems to directly contradict the fact that both CF and TRAD participants were told and monitored to ensure that maximal effort intensities were given during all resistance training sessions, while FE participants were not monitored or given any intensity prescriptions during their workouts. Thus it was expected (based on the secondary hypothesis) to find the opposite result, given the assumption that a lack of intensity prescription in FE would be more likely to result in a training demand below well below MRV, than the ensured repetitive maximal effort training performed by both CF and TRAD.

Additionally, when investigating the specific exercises prescribed to each group, based on the principle of training specificity and the secondary hypothesis, CF was to exhibit a significant change in both upper and lower body power over time, as the CrossFit training program (used to train CF participants) regularly included explosive movements, such as box jumps, wall balls, and push-presses (see Appendix H) that mimicked the movement patterns of the measures used to asses anaerobic power, (i.e. vertical jump test, medicine ball toss test, and upper/lower body Wingate tests). Conversely, TRAD was explicitly prescribed exercises that did not involve any explosive movement of participant bodyweight or external weights applied to participants (see Appendix I), and FE was not prescribed any specific exercises.

There is no clear physiological reason for the lack of adaptation in the two training groups compared to FE (with regard to the observed pre-post changes in muscular power). If the workload was progressive and sufficient to overload the anaerobic energy systems, then under recovery (or "underperformance syndrome", as termed by Budgett, (2000)) could explain the lack of power output improvement in TRAD and CF. It is, however, important to note that, with regards to mean lower body power output (measured during a 30 second Wingate test on a cycle ergometer), 9/10 CF participants exhibited decrements overtime, while only 5/10 participants in TRAD experienced the same change (see Table 4). Thus, the findings regarding power output following training indicate the heterogeneity of the response to TRAD and CF programs (in line with the primary hypothesis). If these participants were exposed to non-functional over-reaching, and therefore required a prolonged period of rest prior to post training assessment, then post-training measures may have been taken while participants were still in an over-reached state, resulting in reduced measures of power output (relative to FE). A period of unloading for this study (to accommodate for fatigue) was followed, however accumulated fatigue due to inadequate rest and recovery throughout the training program may have led some participants to still be fatigued at the time of post-testing (Hoffman, 2002).

Exercise Variety and Effects on Fitness

To understand the results of this study, one might examine the how the types of exercise might have influenced specific fitness results. For example, single element CrossFit workouts (i.e. WODs comprised entirely of either weightlifting exercises or gymnastics exercises or metabolic conditioning exercises) have been shown to result in an acute reduction in the countermovement jump height of college aged participants (regardless of element utilized) (Maté-Muñoz et al., 2017). Other CrossFit studies have found stagnation in jumping test performance following alternative training protocols – for example, Goins et al. (2014) showed that, as in the current study, 6 weeks of CrossFit training (at a frequency of 5 workouts per week) did not yield significant improvements in vertical jump height over time in 19-29 year old moderately active participants. Although other CrossFit investigators have demonstrated improvements in lower body anaerobic power output following a multiple week CrossFit training intervention (Jeffery, 2012), these outcomes were measured using methods that did not involve jumping. Therefore, it may be possible for CrossFit training to improve lower body anaerobic power, but the bulk of empirical evidence in this field to date suggests that this mode of training will negatively affect maximal instantaneous jump height/distance.

These findings can likely be attributed to the high intensity, low rest, cyclical nature (i.e. involving stretch-shortening cycles) of exercises performed during most CrossFit workouts (Maté-Muñoz et al., 2017) resulting in damage at the muscle-tendon insertions of trained muscles (Horita, Komi, Hämäläinen, & Avela, 2003; Ishikawa et al., 2006). This type of damage reduces muscle-tendon stiffness (Horita et al., 2003; Ishikawa et al., 2006), a factor which has been shown to negatively impact jump power (Ishikawa et al., 2006).

Mechanical energy produced by the skeletal muscles during dynamic activities like running and walking is conserved via leg tendons that stretch (i.e. store energy in the form of elastic tension) and then recoil, thereby allowing for the recycling of metabolic energy during cyclic exercise (Cavagna, Saibene, & Margaria, 1964). During running, kinetic and gravitational potential energy is lost as an individual falls to absorb the shock of their foot striking the ground, but subsequently regained as the individual extends their leg to rise back up (Alexander, 2002; Cavagna et al., 1964).

In humans, tendons attached to skeletal muscles have elastic properties that allow for amplification of power produced by skeletal muscles during explosive activities, such as jumping (Konow, Azizi, & Roberts, 2012). The elasticity of tendons makes the recoil speed of these structures significantly faster than the shortening speed of muscles (Alexander, 2002; Ker, 1981); although the amount of energy returned during recoil of a tendon cannot exceed the amount of energy required to initially stretch said tendon, because the same amount of work is performed over a shorter duration of time during elastic recoil, power output is increased (Alexander, 1995; Alexander, 2002). Tendons therefore act as a power amplifier for skeletal muscles (Konow et al., 2012) - one consequence of this relationship is the ability of humans to jump considerably higher (and/or farther) than they otherwise could without highly elastic tendons (Alexander & Vernon, 1975; Alexander, 2002).

These properties of skeletal muscle tendons could explain why the secondary analysis of strength and power outcomes showed that, out of the 4 CF participants in the current study who exhibited decrements in vertical jump over time, only 1 elicited a concomitant decrease in back squat E-1RM from pre- to post-training (see Table 4); while the exercises and intensities commonly utilized during CrossFit WODs appear to be sufficient to incur significant neuromuscular adaptions necessary for increases in strength (at least in the short term) (Barfield et al., 2012; Paine et al., 2010), the cyclical nature of such movements probably produces damage at the muscle tendon unit (Horita et al., 2003; Ishikawa et al., 2006). Consequent reductions in the tendon stiffness of CF participants could have negatively impacted the stretch/recoil capabilities of leg tendons (Ishikawa et al., 2006) – it is plausible that this change in muscle tendon stiffness/elasticity reduced the amount of elastic energy stored in the leg tendons of CF participants during the eccentric/ “down” phase of the countermovement jump, thereby decreasing the amount of power attained through elastic recoil during the concentric/ “up” phased of the jump (Alexander, 2002; Cavagna et al., 1964). Therefore, this potential reduction in leg power may have consequently manifested as a decrease in vertical jump height following CrossFit training in the current study.

However, it may also be that muscle fiber shifts (from type 2x to type 2a) induced through CrossFit modality training negatively influenced instantaneous power (via reduced contraction velocity of trained muscles) (Burke & Edgerton, 1975; Korhonen et al., 2006; J. Wilson et al., 2012). Loss of fibers with the fastest contraction velocity (i.e. type 2x/fast-glycolytic) would probably result in an overall loss in maximum contraction velocity of the trained muscles, based on the strong relationship between muscle fiber composition and whole muscle contractile velocity (Aagaard & Andersen, 1998; Harridge, 1996; Harridge et al., 1996; Tihanyi et al., 1982; Yates & Kamon, 1983).When combined with the presumed insufficient rest and/or recovery between CrossFit workouts and speculated damaged skeletal muscle-tendon structures resulting from repetitive performance of exercises with a cyclical nature (e.g. box jumps, kettlebell swings, and wall balls), this training induced shift in muscle fiber composition may have also contributed to the observed stagnation in vertical jump height of the CF group.

Practical Application and Future Topics of Research

Secondary analyses within the current study demonstrated that CrossFit is a modality of training capable of producing significant improvements in both strength and VO_{2max} in recreationally active adults – if these results are replicable in endurance athletes (who will have higher baseline levels of fitness relative to the "recreationally active" participants of the current study), CrossFit training may offer a time efficient method of eliciting improvements in both musculoskeletal strength and VO_{2max}, thereby improving late race sprint capacity and movement economy (attributes which are critical to determining the outcomes of competitive endurance events) (Beattie et al., 2014; Paton & Hopkins, 2004; Tanaka & Swensen, 1998). Whether or not incorporation of CrossFit into a pre-season or in-season endurance training calendar is beneficial (not to just aerobic power, but also late stage sprint-ability in an endurance race) is therefore an interesting topic for future research.

Specifically, CrossFit might improve late race sprint capacity in endurance competition via reservation of muscle fibers with the fastest possible contraction velocity (i.e. type 2x) during earlier stages of competition. The idea of preferential muscle fiber recruitment related to greater fiber proportionality has been briefly explored in previous literature (Morgan et al., 1995; Tanaka & Swensen, 1998). If a greater relative proportion of type 2a fibers delays recruitment of less prominent type 2x muscle fibers, force output could be maximized at latter stages of endurance sport races (assuming adequate substrate stores support such activity) by reserving muscle fibers with the fastest possible contraction velocity (i.e. type 2x) throughout competition.

Additionally, previous research has suggested that, in order to maximize success in competitive endurance events, athletes need to be capable of sustaining continuous bouts of low intensity exercise, via elevated levels of aerobic fitness (i.e. VO_{2max}) (Bazyler et al., 2015; Hickson, Dvorak, Gorostiaga, Kurowski, & Foster, 1988; Paton & Hopkins, 2004). The work of others further suggests that strength training derived improvements in sprint capacity (following a long duration bout of high intensity exercise) are also critical in determining endurance athlete performance during competitive events (Beattie et al., 2014; Noakes, 1988; Osteras, Helgerud, &

Hoff, 2002; Stone et al., 2006). Based on the findings of the current experiment, CrossFit could therefore offer a training methodology which concurrently enhances both of these attributes – the secondary analyses of the data collected demonstrated that CF experienced significant increases in both VO_{2max} and all measures of muscle strength over time. However, the secondary analyses also revealed a significant decrease in lower body anaerobic power over time for the CF group. Thus, the possibility of CrossFit reducing anaerobic power (possibly via reductions in musculotendinous stiffness following micro trauma to muscle-tendon insertions, and/or over training due to the high volume training schedule recommended by the CFTG, as reported by Outlaw et al. (2014) and Drake et al. (2017)) also has the potential to harm endurance performance. Specifically, explosive power is required during endurance races in order to perform sprints to the finish line, climb hills, and make advances to pass other athletes, and/or fight off advances from athletes attempting to pass, (Tanaka & Swensen, 1998).

As endurance athletes are a population likely to attempt CrossFit in exchange for less time-efficient concurrent training methods (that place endurance and strength workouts on different days, or at different hours of the same day), and the current study demonstrated that CrossFit elicits a mixture of improvements and decrements in fitness variables critically important for determining athlete placement in competitive endurance races, future research in the CrossFit domain should focus on the effect of this mode of training on sport specific outcomes desirable to endurance athletes. Specifically, more research is needed in the CrossFit literature to A. determine which physiological mechanisms and molecular cascades are responsible for the CrossFit induced training adaptations reported to date, B. determine if an isolated endurance training program (i.e. performed without concurrent strength training) results in improvements in VO_{2max} that are superior to those incurred through CrossFit, and lastly, C. report the effect of long term CrossFit training interventions (e.g. >6 weeks) on the fitness attributes investigated in the current study.

Conclusions

The aforementioned mixture of observed adaptations suggests that, due to its multimodal nature, CrossFit can prompt a range of adaptations in physical fitness. However, contradictory to unsupported claims published in the CFTG, a resistance training program (such as CrossFit) that deliberately avoids isolation movements, and instead, prescribes almost entirely compound, “functional” movements (which typically involve whole body exercises), does not appear to be “radically more effective at eliciting nearly any desired fitness result” (Glassman, 2010), or in other words, produce superior gains in all attributes of fitness relative to a more traditional resistance training program (that prescribes isolation exercises).

The secondary analyses revealed that the CF group (who performed CrossFit style resistance training workouts for 6 weeks) experienced significant improvements in upper body push strength, upper body pull strength, leg extension strength, leg flexion strength, lower body general strength, lower body general endurance, and upper body pull endurance outcomes in moderately trained adults. However, because performance of either 6 weeks of traditional style resistance training workouts (by the TRAD group) and/or maintained habitual exercise (by the FE group) elicited post-training means that were not significantly different from CF, it is unclear if CrossFit offers any benefit to improving these particular fitness attributes in the investigated population, relative to more traditional resistance training methods and modalities.

Additionally, because CF incurred significantly greater post-training upper body endurance relative to TRAD, it can also be concludes that CrossFit may provide a superior method for eliciting positive upper body endurance adaptations compared to traditional resistance training in recreationally active adults (at least in the short term). However, as CF was also the only study group to show significant decrements in lower body mean power (recorded during a 30 second Wingate test on a cycle ergometer) over time, and the primary analyses revealed a significantly lower post-training mean lower body anaerobic power of CF (relative to the study groups that were trained using more traditional methods), the CrossFit modality of resistance training appears to be inferior for improving and maintaining levels of lower body anaerobic power in the aforementioned population, relative to more traditional resistance training workouts.

Thus, it is plausible that performing 6 weeks of novel CrossFit workouts (comprised of concurrent strength and endurance training modes) in the current study, incurred a gross (rather than specific) training stimulus. This stimulus (potentially incurred through summation of both strength and endurance training stress), likely induced significant disruption of cellular homeostasis (due to the lack of habituation of CF participants to CrossFit workouts). Consequently, it is possible that CrossFit modality training produced a “generic molecular footprint” (Coffey & Hawley, 2017) in the CF participants of the current study, which subsequently manifested as improvements in both strength (estimated 1-RM) and endurance (VO_{2max}) over time, rather than isolated improvements at either end of the strength/power – endurance spectrum.

These findings therefore build upon the work of previous authors examining the effect of concurrent training on the interference effect, and suggest that, when performed according to the CrossFit format, an incomplete interference effect (which normally follows concurrent training in sedentary individuals) (Nader et al., 2014; Ydfors et al., 2013) can be extended to recreationally active adults, who habitually perform strength and/or aerobic exercise training. However, given the fact that this phenomenon is reversed (i.e. an interference effect is observed) when elite athletes perform concurrent training (MacDougall et al., 1982; Ronnestad, Hansen, & Raastad, 2010), future research should examine the training experience "cut-off", after which performance of concurrent training becomes detrimental to training derived improvements in strength. Additionally, others could investigate if the specific format of CrossFit workouts (which often blends strength and endurance modality exercise within a single session) abolishes the interference effect when performed by previously sedentary individuals or well-trained competitive athletes. If the findings can be extended to populations of elite athletes, the partial absence of an interference effect could also potentially be exploited by strength and conditioning practitioners and professionals as a technique to improve endurance performance.

Chapter 6. Strengths and Limitations of the Study Design

Studies investigating the effects of either acute or long term CrossFit training on aerobic fitness have previously utilized the progressive treadmill test (Bellar et al., 2015; Butcher et al., 2015; Drake et al., 2017; Fernández-Fernández et al., 2015; Kramer, Baur, Spicer, Vukovich, & Ormsbee, 2016; McKenzie, 2015), progressive cycling test (Murawska-Cialowicz et al., 2015), and the 20 m shuttle run test (de Sousa et al., 2016; Eather et al., 2016) as a means of evaluating participant VO2max. Although the shuttle run test has been shown to significantly underestimate VO_{2max} values in adult athletes trained for specific sports (Gibson, Broomhead, Lambert, & Hawley, 1998) and in specific populations (Sproule, Kunalan, McNeill, & Wright, 1993) this test was deemed useful in the current study, due to the more heterogeneous population of "recreationally active" adults.

VO_{2max} was determined as VO2 = -24.4 + 6.0X (where X = maximal aerobic speed (MAS) km/h). When compared to a number of different estimation equations established by various authors in the sports science field (Aandstad, Holme, Berntsen, & Anderssen, 2011; Flouris et al., 2010; Léger & Gadoury, 1989; Ramsbottom, Brewer, & Williams, 1988; Stickland et al., 2003), the above equation (proposed by Léger et al. (1988)) was found to have one of the highest Pearson correlation coefficients (r = 0.68) of all studies investigated in a recent review of predictive VO_{2max} equations (based on 20m shuttle run test performance) (Aandstad et al., 2011).

Although all shuttle run tests were supervised by at least 1 member of the research team, the nature of having multiple participants performing testing at the same time required participants to self-log performances following test termination - use of the Léger et al. (1988) equation to estimate participant VO_{2max} facilitated researchers in limiting error due to participant data reporting mistakes (which may have occurred with the use of more complicated formulas that require memorization of the "last-half-level" (stage) obtained during the test, or more than 1 performance variable). Thus, use of the Léger et al. (1988) equation in the current study provided a valid and reliable means of estimating aerobic fitness, as well as reducing error associated with participant referenced data collection.

In hindsight, having an aerobic training group (that only performed unloaded, endurance modality training during the study) would have allowed greater understanding of how endurance training (in isolation of other training modes) influenced the fitness measures analyzed. Additionally, although TRAD performed a resistance training program that did not include any endurance type work, participants in this group reported performing long duration sports and recreational activities (in addition to supervised resistance training sessions during the study), that would have placed substantial stress on the aerobic system. Additionally, all of this physical activity fell into participant-selected categories of either "moderate" or "vigorous" intensity exercise (i.e. moderate = activity with a session based RPE of 4-6; vigorous = activity with a session based RPE of 7-10). As it was requested that TRAD participants not perform any type of resistance training external to the supervised traditional resistance training sessions, all reported external exercise was presumably aerobic in nature. TRAD reported performing an average of 10150 minutes of supervised resistance training and 3980 minutes of exercise external to the study protocol. Thus, participants in TRAD performed exercise similar in nature to concurrent training (rather than strict strength type training) - resistance training sessions (strength focus) were performed in conjunction with predominantly aerobic exercise sessions (endurance focus) (although aerobic activity was separated from strength workouts by multiple hours or days). Thus, it is possible that the similarities between TRAD and CF in the current study could be explained by the fact that TRAD performed some aerobic exercise in addition to resistance training.

Additional analysis of participant training logs revealed that most participants in all 3 groups performed forms of exercise other than resistance training (e.g. non-loaded training, such as running, swimming, and/or field sports) on their designated rest days, and on the same days as supervised resistance training session; this extra exercise may have inflated the total exercise volume of CF and TRAD participants, pushing them closer to their respective MRV's. Consequently, the supervised workout frequency of up to 4 times per week in both TRAD and CF, when combined with non-supervised recreational aerobic activities of moderate and vigorous intensity, may not have allowed for enough time to recover between training sessions; alternatively, the individual recovery practices of participants in TRAD and CF (which were out of control of the research team) may have been inadequate to allow for sufficient recovery between workouts.

Although every effort was made to ensure that the resistance training stress incurred by CF and TRAD participants was specific and controlled, non-training related factors associated with lifestyle (e.g. sleep, nutrition, hydration, recreational activities, and mental state) were not controlled, due to researcher and resource limitations – additionally, because participants were recruited from a university setting, and ran the study during mid-term and final exam periods of actively enrolled students, uncontrollable participant stress related to exams and other common sources of student anguish may have had an unanticipated effect on the results. However, one resultant strength of the current study is that in many ways, the experiment offers one of the only CrossFit studies to date that examines a realistic scenario of what might happen to individuals in the target population when they first commence CrossFit modality training; by choosing not to control for things like nutrition, non-resistance training forms of exercise, recovery protocols, and lifestyle stress, the conclusions provide insight into what adaptations 18-30 year old, recreationally active adults should expect when commencing CrossFit style training (at a frequency of up to 4 times per week). Consequently, the conclusions have good generalizability to the fitness industry and applied sport science knowledge for training prescriptions of recreationally active healthy adults.

Bibliography

References

Aagaard, P., & Andersen, J. L. (1998). Correlation between contractile strength and myosin heavy chain isoform composition in human skeletal muscle. / correlation entre la force contractile et la composition isoforme des chaines lourdes de myosine dans le muscle squelettique humain. *Medicine & Science in Sports & Exercise, 30*(8), 1217-1222. Retrieved from http://articles.sirc.ca/search.cfm?id=481043; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH481043&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=481043

Aandstad, A., Holme, I., Berntsen, S., & Anderssen, S. A. (2011). *Validity and reliability of the 20 meter shuttle run test in military personnel* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000292783700011&site=eds-live&scope=site

Adams, G. R., Hather, B. M., Baldwin, K. M., & Dudley, G. A. (1993). Skeletal muscle myosin heavy chain composition and resistance training. *Journal of Applied Physiology (Bethesda, Md.: 1985), 74*(2), 911-915. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=8458814&site=eds-live&scope=site

Ahlborg, B., Bergström, J., Ekelund, L. G., & Hultman, E. (1967). Muscle glycogen and muscle electrolytes during prolonged physical exercise. *Acta Physiologica Scandinavica, 70*(2), 129-142. doi:10.1111/j.1748-1716.1967.tb03608.x

Ahmaidi, S., Collomp, K., Caillaud, C., & Prefaut, C. (1992). Maximal and functional aerobic capacity as assessed by two graduated field methods in comparison to laboratory exercise testing in moderately trained subjects. *International Journal of Sports Medicine, 13*(3), 243-248. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH361818&site=eds-live&scope=site; http://www.thieme.com

Alexander, R. M. (1995). Leg design and jumping technique for humans, other vertebrates and insects. *Philosophical Transactions: Biological Sciences, 347*(1321), 235-235. doi:248

Alexander, R. M. (2002). Review: Tendon elasticity and muscle function. *Comparative Biochemistry and Physiology, Part A, 133*, 1001-1011. doi:10.1016/S1095-6433(02)00143-5

Alexander, R. M., & Vernon, A. (1975). The mechanics of hopping by kangaroos (macropodidae). *Journal of Zoology, 177*(2), 265-303. doi:10.1111/j.1469-7998.1975.tb05983.x

Andersen, J. L., & Aagaard, P. (2000). Myosin heavy chain IIX overshoot in human skeletal muscle. *Muscle & Nerve, 23*(7), 1095-1104. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=10883005&site=eds-live&scope=site

Andersen, J. L., & Aagaard, P. (2010). Effects of strength training on muscle fiber types and size; consequences for athletes training for high-intensity sport. *Scandinavian Journal of Medicine & Science in Sports, 20*, 32-38. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=53474874&site=eds-live&scope=site

Apró, W., Wang, L., Pontén, M., Blomstrand, E., & Sahlin, K. (2013). Resistance exercise induced mTORC1 signaling is not impaired by subsequent endurance exercise in human skeletal muscle. *American Journal of Physiology.Endocrinology and Metabolism, 305*(1), E22-E32. doi:10.1152/ajpendo.00091.2013

Apro, W., Moberg, M., Hamilton, D., Apro, W., Moberg, M., Ekblom, B., . . . Holmberg, H. (2015). *Resistance exercise-induced S6K1 kinase activity is not inhibited in human skeletal muscle despite prior activation of AMPK by high-intensity interval cycling* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000351062500004&site=eds-live&scope=site

Armstrong, L. E., & VanHeest, J. L. (2002). The unknown mechanism of the overtraining syndrome: Clues from depression and psychoneuroimmunology. *Sports Medicine, 32*(3), 185-209. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=6179322&site=eds-live&scope=site

Aziz, A. R., & Chuan, T. K. (2004). Correlation between tests of running repeated sprint ability and anaerobic capacity by wingate cycling in multi-sprint sports athletes. *International*

Journal of Applied Sports Sciences, 16(1), 14-22. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=19948220&site=eds-live&scope=site

Baechle, T. R., & Earle, R. W. (2008). *Essentials of strength training and conditioning* Champaign, Ill. : Human Kinetics, c2008; 3rd ed. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.4185841&site=eds-live&scope=site

Baker, D., Nance, S., & Moore, M. (2001a). The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *Journal of Strength & Conditioning Research (Allen Press Publishing Services Inc.), 15*(1), 92-97. Retrieved from http://articles.sirc.ca/search.cfm?id=S-672845; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPHS-672845&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=S-672845; http://www.nsca-lift.org

Baker, D., Nance, S., & Moore, M. (2001b). The load that maximizes the average mechanical power output during explosive bench press throws in highly trained athletes. / la charge qui optimise le rendement de puissance mecanique moyenne pendant des exercices de sauts en squat effectues par des athletes entraines a la puissance. [Save & Add New] *Journal of Strength & Conditioning Research (Allen Press Publishing Services Inc.), 15*(1), 20-24. Retrieved from http://articles.sirc.ca/search.cfm?id=S-672833; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?dir ect=true&db=s3h&AN=SPHS-672833&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=S-672833; http://www.nsca-lift.org

Baláš, J., Pecha, O., Martin, A. J., & Cochrane, D. (2012). Hand–arm strength and endurance as predictors of climbing performance. *European Journal of Sport Science, 12*(1), 16-25. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=71346935&site=eds-live&scope=site

Baldwin, K. M., & Tipton, C. M. (1972). Work and metabolic patterns of fast and slow twitch skeletal muscle contracting in situ. *Pflügers Archiv European Journal of Physiology, 334*(4), 345-356. doi:10.1007/BF00592168

Bamman, M. M., Petrella, J. K., Kim, J. -., Mayhew, D. L., & Cross, J. M. (2007). Cluster analysis tests the importance of myogenic gene expression during myofiber hypertrophy in humans. *Journal of Applied Physiology, 102*(6), 2232-2239. doi:10.1152/japplphysiol.00024.2007

Barfield, J. P., Channell, B., Pugh, C., Tuck, M., & Pendel, D. (2012). Format of basic instruction program resistance training classes: Effect on fitness change in college students. *Physical Educator, 69*(4), 325-341. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ehh&AN=90037801&site=eds-live&scope=site

Bar-Or, O. (1987). The wingate anaerobic test. an update on methodology, reliability and validity. *Sports Medicine, 4*(6), 381-394. Retrieved from http://articles.sirc.ca/search.cfm?id=244720; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH244720&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=244720

Baumgartner, T. A. (2007). *Measurement for evaluation in physical education and exercise science* Boston : McGraw-Hill, c2007; 8th ed. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.3978022&site=eds-live&scope=site

Bazyler, C. D., Abbott, H. A., Bellon, C. R., Taber, C. B., & Stone, M. H. (2015). Strength training for endurance athletes: Theory to practice. *Strength & Conditioning Journal (Lippincott Williams & Wilkins), 37*(2), 1-12. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=101884606&site=eds-live&scope=site

Beattie, K., Kenny, I., Lyons, M., & Carson, B. (2014). The effect of strength training on performance in endurance athletes. *Sports Medicine, 44*(6), 845-865. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=96086423&site=eds-live&scope=site

Bellar, D., Hatchett, A., Judge, L. W., Breaux, M. E., & Marcus, L. (2015). The relationship of aerobic capacity, anaerobic peak power and experience to performance in CrossFit exercise. *Biology of Sport, 32*(4), 315-320. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=112173524&site=eds-live&scope=site

Beneke, R., Pollmann, C., Bleif, I., Leithäuser, R. M., & Hütler, M. (2002). How anaerobic is the wingate anaerobic test for humans? *European Journal of Applied Physiology,* (4-5), 388-392. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edscal&AN=edscal.13861235&site=eds-live&scope=site

Bergeron, M. F., Nindl, B. C., Deuster, P. A., Baumgartner, N., Kane, S. F., Kraemer, W. J., . . . O'Connor, F. (2011). *Consortium for health and military performance and american college of sports medicine consensus paper on extreme conditioning programs in military personnel* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000296859400013&site=eds-live&scope=site

Bergström, J., & Hultman, E. (1967). A study of the glycogen metabolism during exercise in man. *Scandinavian Journal of Clinical and Laboratory Investigation, 19*(3), 218-228. doi:10.3109/00365516709090629

Bompa, T. O., & Haff, G. (2009). *Periodization : Theory and methodology of training* Champaign, IL. : Human Kinetics, c2009; 5th ed. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.4432795&site=eds-live&scope=site

Borms, D., Maenhout, A., & Cools, A. M. (2016). Upper quadrant field tests and isokinetic upper limb strength in overhead athletes. *Journal of Athletic Training (Allen Press), 51*(10), 789-796. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=120395243&site=eds-live&scope=site

Bottinelli, R. (2001). Functional heterogeneity of mammalian single muscle fibres: Do myosin isoforms tell the whole story? *Pflu¨gers Archiv: European Journal of Physiology, 443*(1), 6-17. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=11692261&site=eds-live&scope=site

Bottinelli, R., Pellegrino, M. A., Canepari, M., Rossi, R., & Reggiani, C. (1999). Specific contributions of various muscle fibre types to human muscle performance: An in vitro study. *Journal of Electromyography and Kinesiology, 9*, 87-95. doi:10.1016/S1050-6411(98)00040-6

Brooks, G. A., Fahey, T. D., & Baldwin, K. M. (2005). *Exercise physiology : Human bioenergetics and its applications* Boston : McGraw-Hill, c2005; 4th ed. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.5275046&site=eds-live&scope=site

Brown, N., Bubeck, D., Alt, W., Haeufle, D. F. B., Schmitt, S., Weickenmeier, J., & Kuhl, E. (2017). *Weekly time course of neuro-muscular adaptation to intensive strength training* Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000403499300001&site=eds-live&scope=site

Budgett, R. (2000). Overtraining and chronic fatigue: The unexplained underperformance syndrome (UPS). *International SportMed Journal, 1*(3), 1-10. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=7232578&site=eds-live&scope=site

Burke, R. E., & Edgerton, V. R. (1975). Motor unit properties and selective involvement in movement. *Exercise and Sport Sciences Reviews, 3*(1), 31-81. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0016420729&site=eds-live&scope=site

Bushie, J., & Lobe, C. (2007). *Are we training smart, or just hard?* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000244972900009&site=eds-live&scope=site

Butcher, S. J., Neyedly, T. J., Horvey, K. J., & Benko, C. R. (2015). Do physiological measures predict selected CrossFit® benchmark performance? *Open Access Journal of Sports Medicine, Vol 2015, Iss Default, Pp 241-247 (2015),* , 241. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsdoj&AN=edsdoj.2325ccaaa95f4a2ab73e8c8b6e10a493&site=eds-live&scope=site

Carrithers, J. A., Coker, R. H., Sullivan, D. H., Carroll, C. C., & Trappe, T. A. (2007). Concurrent exercise and muscle protein synthesis: Implications for exercise countermeasures in space. *Aviation Space and Environmental Medicine, 78*(5), 457-462. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-34248220042&site=eds-live&scope=site

Castelli, P. (2017). Determining the maximal recoverable volume of resistance training in tonnage during a strength phase. *WWU Graduate School Collection, 603*

Cavagna, G. A., Saibene, F. P., & Margaria, R. (1964). Mechanical work in running. *Journal of Applied Physiology, 19*, 249-256. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=14155290&site=eds-live&scope=site

Chilibeck, P. D., Calder, A. W., Sale, D. G., & Webber, C. E. (1998). A comparison of strength and muscle mass increases during resistance training in young women. *European Journal of Applied Physiology and Occupational Physiology, 77*(1-2), 170-175. doi:10.1007/s004210050316

Coffey, V. G., & Hawley, J. A. (2007). The molecular bases of training adaptation. *Sports Medicine, 37*(9), 737-763. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=26493156&site=eds-live&scope=site

Coffey, V. G., & Hawley, J. A. (2017). *Concurrent exercise training: Do opposites distract?* Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000400357800016&site=eds-live&scope=site

Coffey, V. G., Hawley, J. A., Jemiolo, B., Trappe, S. W., Edge, J., & Garnham, A. P. (2009). *Effect of consecutive repeated sprint and resistance exercise bouts on acute adaptive responses in human skeletal muscle* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000271371900025&site=eds-live&scope=site

Comfort, P., & Mcmahon, J. J. (2015). Reliability of maximal back squat and power clean performances in inexperienced athletes. *Journal of Strength and Conditioning Research, 29*(11), 3089-3096. doi:10.1519/JSC.0000000000000815

Coyle, E. F., Coggan, A. R., Hopper, M. K., & Walters, T. J. (1988). Determinants of endurance in well-trained cyclists. *Journal of Applied Physiology, 64*(6), 2622-2630. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0023914521&site=eds-live&scope=site

Damas, F., Phillips, S., Vechin, F., & Ugrinowitsch, C. (2015). A review of resistance training-induced changes in skeletal muscle protein synthesis and their contribution to hypertrophy. *Sports Medicine, 45*(6), 801-807. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=102810075&site=eds-live&scope=site

Darrall-Jones, J., Jones, B., & Till, K. (2015). Anthropometric and physical profiles of english academy rugby union players. *Journal of Strength and Conditioning Research, 29*(8), 2086-2096. doi:10.1519/JSC.0000000000000872

de Sousa, A. F. M., dos Santos, G. B., dos Reis, T., Valerino, A. J. R., Del Rosso, S., & Boullosa, D. A. (2016). Differences in physical fitness between recreational CrossFit® and resistance trained individuals. *Journal of Exercise Physiology Online, 19*(5), 112-122. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=118532272&site=eds-live&scope=site

Dong-il Seo, Kim, E., Fahs, C. A., Rossow, L., Young, K., Ferguson, S. L., . . . Wi-Young So. (2012). Reliability of the one-repetition maximum test based on muscle group and gender. *Journal of Sports Science & Medicine, 11*(2), 221-225. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=77870273&site=eds-live&scope=site

Drake, N., Smeed, J., Carper, M. J., & Crawford, D. A. (2017). Effects of short-term CrossFit™ training: A magnitude-based approach. *Journal of Exercise Physiology Online, 20*(2), 111-133. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=122655655&site=eds-live&scope=site

Dudley, G., & Murray, T. F. (1982). Energy for sport. *National Strength Coaches Association Journal, 4*(3), 14-15. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-84945009528&site=eds-live&scope=site

Eather, N., Morgan, P. J., & Lubans, D. R. (2016). Improving health-related fitness in adolescents: The CrossFit teens™ randomised controlled trial. *Journal of Sports Sciences, 34*(3), 209-223. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=111588343&site=eds-live&scope=site

Ebben, W. P., Kindler, A. G., Chirdon, K. A., Jenkins, N. C., Polichnowski, A. J., & Ng, A. V. (2004). The effect of high-load vs. high-repetition training on endurance performance. *Journal of Strength & Conditioning Research, 18*(3), 513-517. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=14220300&site=eds-live&scope=site

Ericson, M. O., Nisell, R., Arborelius, U. P., & Ekholm, J. (1985). Muscular activity during ergometer cycling. *Scandinavian Journal of Rehabilitation Medicine, 17*(2), 53-61. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=107587639&site=eds-live&scope=site

Esbjörnsson, M., Hellsten-Westing, Y., Balsom, P. D., Sjödin, B., & Jansson, E. (1993). Muscle fibre type changes with sprint training: Effect of training pattern. *Acta Physiologica Scandinavica, 149*(2), 245-246. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=8266814&site=eds-live&scope=site

Espana-Romero, V., Porcel, F., Artero, E. G., Jimenez-Pavon, D., Sainz, A. G., Garzon, M., & Ruiz, J. R. (2009). *Climbing time to exhaustion is a determinant of climbing performance in high-level sport climbers* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000271199300003&site=eds-live&scope=site

Essen, B., Pernow, B., Saltin, B., & Gollnick, P. D. (1973). Muscle glycogen content and lactate uptake in exercising muscles. () Retrieved from http://articles.sirc.ca/search.cfm?id=18516; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH18516&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=18516

Farrar, R. E., Mayhew, J. L., & Koch, A. J. (2010). Oxygen cost of kettlebell swings. *Journal of Strength and Conditioning Research, 24*(4), 1034-1036. doi:10.1519/JSC.0b013e3181d15516

Fernández-Fernández, J., Sabido-Solana, R., Moya, D., Sarabia, J. M., & Moya, M. (2015). Acute physiological responses during crossfit® workouts. *Motricidad: European Journal of Human Movement, 35*, 114-124. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=114714428&site=eds-live&scope=site

Flouris, A. D., Metsios, G. S., Famisis, K., Geladas, N., Koutedakis, Y., Flouris, A. D., . . . Koutedakis, Y. (2010). Prediction of VO2max from a new field test based on portable indirect calorimetry. *Journal of Science & Medicine in Sport, 13*(1), 70-73. doi:10.1016/j.jsams.2009.04.002

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Medicine,* (2), 145. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.200843966&site=eds-live&scope=site

Forbes, S. C., Kennedy, M. D., Boule, N. B., & Bell, G. (2014). Determination of the optimal load setting for arm crank anaerobic testing in men and women. *International Journal of Sports Medicine, 35*(10), 835-839. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=97598169&site=eds-live&scope=site

Frontera, W. R., Meredith, C. N., O'Reilly, K. P., & Evans, W. J. (1990). Strength training and determinants of $\dot{V}$O2(max) in older men. *Journal of Applied Physiology, 68*(1), 329-333. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0025096985&site=eds-live&scope=site

Fry, A. C., & Kraemer, W. J. (1997). Resistance exercise overtraining and overreaching: Neuroendocrine responses. *Sports Medicine,* (2), 106. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsovi&AN=edsovi.00007256.199723020.00004&site=eds-live&scope=site

Fry, A. C. (2004). The role of resistance exercise intensity on muscle fibre adaptations. *Sports Medicine, 34*(10), 663-679. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=14281653&site=eds-live&scope=site

Fyfe, J., Bishop, D., & Stepto, N. (2014). Interference between concurrent resistance and endurance exercise: Molecular bases and the role of individual training variables. *Sports Medicine, 44*(6), 743-762. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=96086418&site=eds-live&scope=site

Gacesa, P., Jelena, Z., Klasnja, A. V., & Grujic, N. G. (2013). Changes in strength, endurance, and fatigue during a resistance-training program for the triceps brachii muscle. *Journal of Athletic Training (Allen Press), 48*(6), 804-809. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=92723883&site=eds-live&scope=site

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I., . . . Swain, D. P. (2011). Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Medicine & Science in Sports & Exercise, 43*(7), 1334-1359 26p. doi:10.1249/MSS.0b013e318213fefb

Gerhart, D. H. (2014). *A comparison of CrossFit training to traditional anaerobic resistance training in terms of selected fitness domains representative of overall athletic performance* TopSCHOLAR®, 2014-05-23T18:41:28Z. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsoai&AN=edsoai.883886035&site=eds-live&scope=site; http://digitalcommons.wku.edu/ijesab/vol9/iss2/26

Gibala, M. J., & Jones, A. M. (2013). Physiological and performance adaptations to high-intensity interval training. *Nestle Nutrition Institute Workshop Series, 76*, 51-60. doi:10.1159/000350256

Gibala, M. J., & McGee, S. L. (2008). *Metabolic adaptations to short-term high-intensity interval training: A little pain for a lot of gain?* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000254477700003&site=eds-live&scope=site

Gibson, S. C., Broomhead, S., Lambert, M. I., & Hawley, J. A. (1998). Prediction of maximal oxygen uptake from a 20-m shuttle run as measured directly in runners and squash players. *Journal of Sports Sciences, 16*(4), 331-335. doi:10.1080/02640419808559361

Gillen, J. B., & Gibala, M. J. (2014). Is high-intensity interval training a time-efficient exercise strategy to improve health and fitness? *Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquee, Nutrition Et Metabolisme, 39*(3), 409-412. doi:10.1139/apnm-2013-0187

Glassman, G. (2010). The CrossFit training guide.*4*

Goins, J., Richardson, M. T., Wingo, J., Hodges, G., Leaver-Dunn, D., & Leeper, J. (2014). *Physiological and performance effects of crossfit* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000339115901429&site=eds-live&scope=site

Gollnick, P. D., Armstrong, R. B., Saltin, B., Saubert 4th., C. W., Sembrowich, W. L., & Shepherd, R. E. (1973). Effect of training on enzyme activity and fiber composition of human skeletal muscle. *Journal of Applied Physiology, 34*(1), 107-111. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0015535972&site=eds-live&scope=site

Goodman, J. M., Liu, P. P., & Green, H. J. (2005). Left ventricular adaptations following short-term endurance training. *Journal of Applied Physiology (Bethesda, Md.: 1985), 98*(2), 454-460. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=15448118&site=eds-live&scope=site

Grant, S., Hynes, V., Whittaker, A., & Aitchison, T. (1996). Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *Journal of Sports Sciences, 14*(4), 301-309. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=7613530&site=eds-live&scope=site

Green, H. J., Barr, D. J., Fowles, J. R., Sandiford, S. D., & Ouyang, J. (2004). Malleability of human skeletal muscle na(+)-K(+)-ATPase pump with short-term training. *Journal of*

Applied Physiology (Bethesda, Md.: 1985), 97(1), 143-148. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=15220317&site=eds-live&scope=site

Hagberg, J. M., Goldberg, A. P., Lakatta, L., O'Connor,F.C., Becker, L. C., Lakatta, E. G., & Fleg, J. L. (1998). Expanded blood volumes contribute to the increased cardiovascular performance of endurance-trained older men. *Journal of Applied Physiology (Bethesda, Md.: 1985), 85*(2), 484-489. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=9688724&site=eds-live&scope=site

Hakkinen, K., Alen, M., Kraemer, W. J., Gorostiaga, E., Izquierdo, M., Rusko, H., . . . Paavolainen, L. (2003). Neuromuscular adaptations during concurrent strength and endurance training versus strength training. / adaptations neuromusculaires lors d ' un entrainement d ' endurance en concurrence avec un entrainement de musculation par rapport a un entrainement de musculation seul. *European Journal of Applied Physiology, 89*(1), 42-52. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPHS-945073&site=eds-live&scope=site

Harridge, S. (1996). In Marconnet P. (Ed.), *The muscle contractile system and its adaptation to training* Karger. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsbl&AN=CN014006159&site=eds-live&scope=site

Harridge, S., Bottinelli, R., Canepari, M., Pellegrino, M., Reggiani, C., Esbjörnsson, M., & Saltin, B. (1996). Whole-muscle and single-fibre contractile properties and myosin heavy chain isoforms in humans. *Pflugers Archiv European Journal of Physiology, 432*(5), 913. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=73153242&site=eds-live&scope=site

Hather, B. M., A., Tesch, P. A., A., Buchanan, P., A., & Dudley, G. A., A. (1991). Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiologica Scandinavica,* , 177. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsswe&AN=edsswe.oai.DiVA.org.miun.17917&site=eds-live&scope=site

Hawley, J. A. (2002). Adaptations of skeletal muscle to prolonged, intense endurance training. *Clinical & Experimental Pharmacology & Physiology, 29*(3), 218-222. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=6281923&site=eds-live&scope=site

Hedelin, R., Kentta, G., Wiklund, U., Bjerle, P., & Henriksson-Larsen, K. (2000). Short-term overtraining: Effects on performance, circulatory responses, and heart rate variability. *Medicine and Science in Sports and Exercise, 32*(8), 1480-1484. doi:10.1097/00005768-200008000-00017

Hermans, E., Andersen, V., & Saeterbakken, A. H. (2017). The effects of high resistance–few repetitions and low resistance–high repetitions resistance training on climbing performance. *European Journal of Sport Science, 17*(4), 378-385. doi:10.1080/17461391.2016.1248499

Hermansen, L., Hultman, E., & Saltin, B. (1967). Muscle glycogen during prolonged severe exercise. *Acta Physiologica Scandinavica, 71*(2), 129-139. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0014143206&site=eds-live&scope=site

Hermansen, L., Maehlum, S., Pruett, E. D., Vange, O., & Waldum, H. (1973). Lactate removal at rest and during exercise. () Retrieved from https://secure.sportquest.com/su.cfm?articleno=18511&title=18511; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH18511&site=eds-live&scope=site; https://secure.sportquest.com/su.cfm?articleno=18511&title=18511

Hickson, R., Dvorak, B., Gorostiaga, E., Kurowski, T., & Foster, C. (1988). Potential for strength and endurance training to amplify endurance performance. *Journal of Applied Physiology (Bethesda, Md.: 1985), 65*(5), 2285-2290. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=3209573&site=eds-live&scope=site

Hickson, R. (1980). Interference of strength development by simultaneously training for strength and endurance. *European Journal of Applied Physiology & Occupational Physiology, 45*(2), 255. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=73049928&site=eds-live&scope=site

Hoffman, J. (2002). *Physiological aspects of sport training and performance* Champaign, IL : Human Kinetics, c2002. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.2603554&site=eds-live&scope=site

Holloszy, J. O. (1975). Adaptation of skeletal muscle to endurance exercise. *Medicine and Science in Sports and Exercise, 7*(3), 155-164. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0016773679&site=eds-live&scope=site

Holloszy, J. O., & Coyle, E. F. (2016). Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *Journal of Applied Physiology, 121*(6), 831-838. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-85007484094&site=eds-live&scope=site

Hood, M. S., Little, J. P., Myslik, F., Gibala, M. J., & Tarnopolsky, M. A. (2011). Low-volume interval training improves muscle oxidative capacity in sedentary adults. *Medicine and Science in Sports and Exercise, 43*(10), 1849-1856. doi:10.1249/MSS.0b013e3182199834

Hoppeler, H., & Flueck, M. (2003). Plasticity of skeletal muscle mitochondria: Structure and function. / plasticite de la mitochondrie du muscle : Structure et fonction. *Medicine & Science in Sports & Exercise, 35*(1), 95-104. Retrieved from http://articles.sirc.ca/search.cfm?id=S-863747; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPHS-863747&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=S-863747; http://www.wwilkins.com

Horita, T., Komi, P. V., Hämäläinen, I., & Avela, J. (2003). Exhausting stretch-shortening cycle (SSC) exercise causes greater impairment in SSC performance than in pure concentric performance. *European Journal of Applied Physiology, 88*(6), 527-534. doi:10.1007/s00421-002-0716-z

Ishikawa, M., Dousset, E., Avela, J., Kyröläinen, H., Kallio, J., Linnamo, V., . . . Nicol, C. (2006). Changes in the soleus muscle architecture after exhausting stretch-shortening cycle exercise in humans. *European Journal of Applied Physiology, 97*(3), 298-306. doi:10.1007/s00421-006-0180-2

Isratel, M., Hoffman, J., & Smith, C. W. (2016). *Scientific principles of strength training* Juggernaut Training Systems.

Jaafar, H., Rouis, M., Coudrat, L., Attiogbé, E., Driss, T., & Vandewalle, H. (2014). Effects of load on wingate test performances and reliability. *Journal of Strength and Conditioning Research, 28*(12), 3462-3468. doi:10.1519/JSC.0000000000000575

Jeffery, C. (2012). Crossfit effectiveness on fitness levels and demonstration of successful program objectives.

Jorfeldt, L. (1970). Metabolism of L(plus)-lactate in human skeletal muscle during exercise. *Acta Physiologica Scandinavica.Supplementum, 338*, 1-67. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=4917455&site=eds-live&scope=site

Kamandulis, S., Bruzas, V., Mockus, P., Stasiulis, A., Snieckus, A., & Venckunas, T. (2018). Sport-specific repeated sprint training improves punching ability and upper-body aerobic power in experienced amateur boxers. *Journal of Strength and Conditioning Research, 32*(5), 1214-1221. doi:10.1519/JSC.0000000000002056

Karlsson, J., Nordesjö, L. O., Jorfeldt, L., & Saltin, B. (1972). Muscle lactate, ATP, and CP levels during exercise after physical training in man. *Journal of Applied Physiology, 33*(2), 199-203. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0015383398&site=eds-live&scope=site

Karlsson, J., & Saltin, B. (1970). Lactate, ATP, and CP in working muscles during exhaustive exercise in man. *Journal of Applied Physiology, 29*(5), 596-602. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=5474850&site=eds-live&scope=site

Karp, J. R. (2001). Muscle fiber types and training. *Strength and Conditioning Journal, 23*(5), 21-26. doi:10.1519/00126548-200110000-00004

Ker, R. F. (1981). Dynamic tensile properties of the plantaris tendon of sheep (ovis aries). *Journal of Experimental Biology, 93*, 283-302. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0019600771&site=eds-live&scope=site

Keul, J. (1973). Muscle metabolism during long lasting exercise. () Retrieved from http://articles.sirc.ca/search.cfm?id=18502; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH18502&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=18502

Keul, J., Haralambie, G., Arnold, T., & Schumann, W. (1974). Heart rate and energy-yielding substrates in blood during long-lasting running. *European Journal of Applied Physiology and Occupational Physiology, 32*(4), 279-289. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=4852233&site=eds-live&scope=site

Keul, J., Doll, E., & Keppler, D. (1972). *Energy metabolism of human muscle* Basel, S. Karger, 1972. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.1952699&site=eds-live&scope=site

Kliszczewicz, B., Snarr, R. L., & Esco, M. (2014). Metabolic and cardiovascular response to the CrossFit workout ‘Cindy’: A pilot study. *Journal of Sport and Human Performance, 2*(2), 1-9. doi:10.12922/jshp.0038.2014

Kliszczewicz, B., John, Q. C., Daniel, B. L., Gretchen, O. D., Michael, E. R., & Kyle, T. J. (2015). Acute exercise and oxidative stress: CrossFit™ vs. treadmill bout. *Journal of*

Human Kinetics, 47(1), 81-90. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=110525487&site=eds-live&scope=site

Knapik, J. J. (2015). Extreme conditioning programs: Potential benefits and potential risks. *Journal of Special Operations Medicine: A Peer Reviewed Journal for SOF Medical Professionals, 15*(3), 108-113. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=26360365&site=eds-live&scope=site

Koenig, D., Huonker, M., Schmid, A., Halle, M., Berg, A., & Keul, J. (2001). Cardiovascular, metabolic, and hormonal parameters in professional tennis players. / parametres cardiovasculaires, metaboliques et hormonaux chez des joueurs de tennis professionnels. *Medicine & Science in Sports & Exercise, 33*(4), 654-658. Retrieved from http://articles.sirc.ca/search.cfm?id=S-729129; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPHS-729129&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=S-729129; http://www.wwilkins.com

Konow, N., Azizi, E., & Roberts, T. J. (2012). Muscle power attenuation by tendon during energy dissipation. *Proceedings: Biological Sciences,* (1731), 1108. doi:10.1098/rspb.2011.1435

Korhonen, M. T., Cristea, A., Alén, M., Häkkinen, K., Sipilä, S., Mero, A., . . . Suominen, H. (2006). Aging, muscle fiber type, and contractile function in sprint-trained athletes. *Journal* *of Applied Physiology, 101*(3), 906-917. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=22347756&site=eds-live&scope=site

Kraemer, W. J., Adams, K., Cafarelli, E., Dudley, G. A., Dooly, C., Feigenbaum, M. S., . . . Triplett-McBride, T. (2002). *Joint position statement: Progression models in resistance training for healthy adults* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000173739100027&site=eds-live&scope=site

Kraemer, W. J., & Gotshalk, L. A. (2000). Physiology of american football. In W. E. Garrett, & D. T. Kirkendall (Eds.), *Exercise and sport science.* (1st ed., pp. 795-813). Philadelphia, PA: Lippincott Williams & Wilkins.

Kraemer, W. J., Nindl, B. C., Ratamess, N. A., Gotshalk, L. A., Volek, J. S., Fleck, S. J., . . . Hakkinen, K. (2004). Changes in muscle hypertrophy in women with periodized resistance training. *Medicine & Science in Sports & Exercise, 36*(4), 697-708. Retrieved from http://articles.sirc.ca/search.cfm?id=S-953850; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPHS-953850&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=S-953850; http://www.wwilkins.com

Kramer, S. J., Baur, D. A., Spicer, M. T., Vukovich, M. D., & Ormsbee, M. J. (2016). The effect of six days of dietary nitrate supplementation on performance in trained CrossFit athletes. *Journal of the International Society of Sports Nutrition, 13*, 1-7. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=119464555&site=eds-live&scope=site

Laffaye, G., Collin, J. M., Levernier, G., & Padulo, J. (2014). *Upper-limb power test in rock-climbing* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000338032100006&site=eds-live&scope=site

Lee, D., Artero, E. G., Sui, X., & Blair, S. N. (2010). Mortality trends in the general population: The importance of cardiorespiratory fitness. *Journal of Psychopharmacology (Oxford, England), 24*(4), 27-35. doi:10.1177/1359786810382057

Léger, L., Lambert, J., Goulet, A., Rowan, C., & Dinelle, Y. (1984). Aerobic capacity of 6 to 17-year-old quebecois--20 meter shuttle run test with 1 minute stages. *Canadian Journal of Applied Sport Sciences.Journal Canadien Des Sciences Appliquees Au Sport, 9*(2), 64-69. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-18144441125&site=eds-live&scope=site

Léger, L., & Gadoury, C. (1989). Validity of the 20 m shuttle run test with 1 min stages to predict VO2max in adults. *Canadian Journal of Sport Sciences = Journal Canadien Des Sciences Du Sport, 14*(1), 21-26. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0024635623&site=eds-live&scope=site

Léger, L., & Lambert, J. (1982). A maximal multistage 20-m shuttle run test to predict VO2 max. *European Journal of Applied Physiology and Occupational Physiology, 49*(1), 1-12. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=7201922&site=eds-live&scope=site

Leger, L. A., Mercier, D., Gadoury, C., & Lambert, J. (1988). The multistage 20 metre shuttle run test for aerobic fitness. *Journal of Sports Sciences (Print),* (2), 93. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edscal&AN=edscal.7196889&site=eds-live&scope=site

Lemyre, P., Roberts, G. C., & Stray-Gundersen, J. (2007). Motivation, overtraining, and burnout: Can self-determined motivation predict overtraining and burnout in elite athletes? *European Journal of Sport Science, 7*(2), 115-126. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=26055815&site=eds-live&scope=site

Leveritt, M., Logan, P. A., Abernethy, P. J., & Barry, B. (2003). Concurrent strength and endurance training: The influence of dependent variable selection. *Journal of Strength and Conditioning Research, 17*(3), 503-508. doi:10.1519/1533-4287(2003)0172.0.CO;2

Löfquist, I. (2017). *Differences in muscle activity during the chin-up versus lat pulldown exercise. an electromyographic study.* (Unpublished Bachelor's Programme in Exercise Biomedicine.). Halmstad University, Halmstad, Sweden. Retrieved from http://www.diva-portal.org/smash/get/diva2:1119323/FULLTEXT02

Lubomirov Michailov, M., Morrison, A., Mitkov Ketenliev, M., & Petkova Pentcheva, B. (2015). A sport-specific upper-body ergometer test for evaluating submaximal and maximal parameters in elite rock climbers. *International Journal of Sports Physiology & Performance, 10*(3), 374-380. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=101756517&site=eds-live&scope=site

Lundberg, T. R., Fernandez-Gonzalo, R., Gustafsson, T., & Tesch, P. A. (2012). Aerobic exercise alters skeletal muscle molecular responses to resistance exercise. *Medicine & Science in Sports & Exercise, 44*(9), 1680-1688. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=79332780&site=eds-live&scope=site

MacDougall, J. D., Sale, D. G., Elder, G. C. B., & Sutton, J. R. (1982). Muscle ultrastructural characteristics of elite powerlifters and bodybuilders. *European Journal of Applied Physiology and Occupational Physiology, 48*(1), 117-126. doi:10.1007/BF00421171

Malisoux, L., Francaux, M., Nielens, H., & Theisen, D. (2006). Stretch-shortening cycle exercises: An effective training paradigm to enhance power output of human single muscle fibers. *Journal of Applied Physiology, 100*(3), 771-779. doi:10.1152/japplphysiol.01027.2005

Manca, A., Dragone, D., Deriu, F., Dvir, Z., Mureddu, G., & Bua, G. (2017). *Time course of strength adaptations following high-intensity resistance training in individuals with multiple sclerosis* Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000398251400012&site=eds-live&scope=site

Maté-Muñoz, J. L., Lougedo, J. H., Barba, M., García-Fernández, P., Garnacho-Castaño, M. V., & Domínguez, R. l. (2017). Muscular fatigue in response to different modalities of CrossFit sessions. *PLoS ONE, 12*(7), 1-17. doi:10.1371/ journal.pone.0181855

Mayorga-Vega, D., Aguilar-Soto, P., & Viciana, J. (2015). Criterion-related validity of the 20-M shuttle run test for estimating cardiorespiratory fitness: A meta-analysis. *Journal of Sports Science & Medicine, 14*(3), 536-547. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=109133561&site=eds-live&scope=site

McArdle, W. D., Katch, F. I., & Katch, V. L. (2010). *Exercise physiology : Nutrition, energy, and human performance* Baltimore, MD : Lippincott Williams & Wilkins, c2010; 7th ed. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.4454778&site=eds-live&scope=site

McCafferty, W. B., & Horvath, S. M. (1977). Specificity of exercise and specificity of training: A subcellular review. *Research Quarterly of the American Alliance for Health, Physical Education and Recreation, 48*(2), 358-371. doi:10.1080/10671315.1977.10615433

McKenzie, M. J. (2015). Crossfit improves measures of muscular strength and power in active young females: 2912 board #227 may 29, 3: 30 PM - 5: 00 PM. *Medicine & Science in Sports & Exercise,* (5), 797. doi:10.1249/01.mss.0000466164.99273.92

McLester, J. R., Green, J. M., & Chouinand, J. L. (2004). Effects of standing vs. seated posture on repeated wingate performance. *Journal of Strength & Conditioning Research, 18*(4), 816-820. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=15255958&site=eds-live&scope=site

Mcweeny, D. (2013). Fitness testing in varsity cross country skiing athletes (unpublished).

Méndez-Villanueva, A., Perez-Landaluce, J., Fernandez-García, B., Ortolano, R., Terrados, N., Bishop, D., & Leibar, X. (2005). Upper body aerobic fitness comparison between two groups of competitive surfboard riders. *Journal of Science and Medicine in Sport, 8*(1), 43-51. doi:10.1016/S1440-2440(05)80023-4

Mermier, C. M., Janot, J. M., Parker, D. L., & Swan, J. G. (2000). Physiological and anthropometric determinants of sport climbing performance. *British Journal of Sports Medicine, 34*(5), 359-366. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=66948705&site=eds-live&scope=site

Meyer, M., Sundaram, S., & Schafhalter-Zoppoth, I. (2017). Exertional and CrossFit-induced rhabdomyolysis. *Clinical Journal of Sport Medicine,* doi:10.1097/JSM.0000000000000480

Moore, R. L., & Palmer, B. M. (1999). Exercise training and cellular adaptations of normal and diseased hearts. *Exercise and Sport Sciences Reviews, 27*, 285-315. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0033287738&site=eds-live&scope=site

Morgan, D. W., Bransford, D. R., Costill, D. L., Daniels, J. T., Howley, E. T., & Krahenbuhl, G. S. (1995). Variation in the aerobic demand of running among trained and untrained subjects. *Medicine & Science in Sports & Exercise, 27*(3), 404-409. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=107201221&site=eds-live&scope=site

Morris, A. F., McCafferty, W. B., & Edington, D. W. (1974a). Metabolism in running training. 1. energy source utilization. 2. training for oxygen shortage. *Modern Athlete & Coach, 12*(5), 2-6. Retrieved from http://articles.sirc.ca/search.cfm?id=13977; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH13977&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=13977

Morris, A. F., McCafferty, W. B., & Edington, D. W. (1974b). Tapping energy sources of track athletes. *Track Technique, 57*, 1825-1825. Retrieved from http://articles.sirc.ca/search.cfm?id=13916; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH13916&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=13916

Mullins, N. (2015). CrossFit: Remember what you have learned; apply what you know. *Journal of Exercise Physiology Online,* (6), 32. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.438289987&site=eds-live&scope=site

Murach, K. A., & Bagley, J. R. (2016). *Skeletal muscle hypertrophy with concurrent exercise training: Contrary evidence for an interference effect* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000383553100001&site=eds-live&scope=site

Murawska-Cialowicz, E., Wojna, J., & Zuwala-Jagiello, J. (2015). **Crossfit training changes brain-derived neurotrophic factor and irisin levels at rest, after wingate and progressive tests, and improves aerobic capacity and body composition of young physically active men and women.** *Journal of Physiology and Pharmacology, 66*(6), 811-821.

Nader, G. A., von Walden, F., Liu, C., Lindvall, J., Gutmann, L., Pistilli, E. E., & Gordon, P. M. (2014). Resistance exercise training modulates acute gene expression during human skeletal muscle hypertrophy. *Journal of Applied Physiology (Bethesda, Md.: 1985), 116*(6), 693-702. doi:10.1152/japplphysiol.01366.2013

Nader, G. A. (2006). Concurrent strength and endurance training: From molecules to man. *Medicine & Science in Sports & Exercise,* (11), 1965. doi:10.1249/01.mss.0000233795.39282.33

Negra, Y., Hammami, M., Chelly, M. S., Hachana, Y., Chaabene, H., & Stöggl, T. (2016). Effectiveness and time-course adaptation of resistance training vs. plyometric training in prepubertal soccer players. *Journal of Sport and Health Science,* doi:10.1016/j.jshs.2016.07.008

Noakes, T. D. (1988). Implications of exercise testing for prediction of athletic performance: A contemporary perspective. / implications de tests d' exercices pour determiner la performance athletique: Une perspective contemporaine. *Medicine & Science in Sports & Exercise, 20*(4), 319-330. Retrieved from http://articles.sirc.ca/search.cfm?id=227077; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH227077&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=227077

O'Hara, R., Schlub, J., Khan, M., & Pohlman, R. (2004). Leg resistance training: Effects upon VO2peak and skeletal muscle myoplasticity. *Journal of Exercise Physiology Online, 7*(5), 27-43. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-14644392910&site=eds-live&scope=site

O'Hara, R. B., Serres, J., Wright, B., Traver, K. L., Vojta, C., & Eveland, E. (2012). The influence of nontraditional training modalities on physical performance: Review of the literature. *Aviation Space and Environmental Medicine, 83*(10), 985-990. doi:10.3357/ASEM.3376.2012

Osteras, H., Helgerud, J., & Hoff, J. (2002). Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *European Journal of Applied Physiology, 88*(3), 255-263. Retrieved from https://secure.sportquest.com/su.cfm?articleno=S-947122&title=S-947122; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?dir ect=true&db=s3h&AN=SPHS-947122&site=eds-live&scope=site; https://secure.sportquest.com/su.cfm?articleno=S-947122&title=S-947122

Outlaw, J. J., Wilborn, C. D., Hayward, S. E., Urbina, S. L., Taylor, L. W., Foster, C. A., & Smith-Ryan, A. (2014). *Effects of a pre-and post-workout protein-carbohydrate supplement in trained crossfit individuals* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000359055900001&site=eds-live&scope=site

Paine, J., Uptgraft, J., & Wylie, R. (2010). *CrossFit study, may 2010* Fort Leavenworth, KS : the Command and General Staff College; 2010. Retrieved from http://library.crossfit.com/free/pdf/CFJ_USArmy_Study.pdf

Parikh, C., & Arora, M. (2014). To develop muscle strength index for establishing norms and comparison of muscle strength for indian recreational collegiate and sedentary college students. *International Journal of Therapies & Rehabilitation Research, 3*(4), 9-18. doi:10.5455/ijtrr.00000037

Pate, R. R., Burgess, M. L., Woods, J. A., Ross, J. G., & Baumgartner, T. (1993). Validity of field tests of upper body muscular strength. *Research Quarterly for Exercise and Sport, 64*(1), 17-24. doi:10.1080/02701367.1993.10608774

Paton, C. D., & Hopkins, W. G. (2004). Effects of high-intensity training on performance and physiology of endurance athletes. *Sportscience,* , 25. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.165819925&site=eds-live&scope=site

Patterson, D. D., & Peterson, D. F. (2004). Vertical jump and leg power norms for young adults. *Measurement in Physical Education & Exercise Science, 8*(1), 33-41. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=12920557&site=eds-live&scope=site

Paul, P., & Holmes, W. L. (1975). Free fatty acid and glucose metabolism during increased energy expenditure and after training. *Medicine and Science in Sports, 7*(3), 176-183. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=1207430&site=eds-live&scope=site

Pelzer, T., Ullrich, B., & Pfeiffer, M. (2017). Periodization effects during short-term resistance training with equated exercise variables in females. *European Journal of Applied Physiology, 117*(3), 441-454. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=121742675&site=eds-live&scope=site

Pescatello, L. S. (2014). *ACSM's guidelines for exercise testing and prescription* Philadelphia : Wolters Kluwer/Lippincott Williams & Wilkins Health, c2014; 9th ed. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.6661076&site=eds-live&scope=site

Petré, H., Löfving, P., & Psilander, N. (2018). The effect of two different concurrent training programs on strength and power gains in highly-trained individuals. *Journal of Sports Science and Medicine, 17*(2), 167-173. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsdoj&AN=edsdoj.98f5fdb8a1a94a448d67961696098d04&site=eds-live&scope=site

Pickett, C. W., Nosaka, K., Zois, J., Hopkins, W. G., J, A., & Blazevich. (2017). Maximal upper body strength and oxygen uptake are associated with performance in high-level 200-M sprint kayakers. *Journal of Strength and Conditioning Research,* doi:10.1519/JSC.0000000000002398

Pollock, M. L., Gaesser, G. A., Butcher, J. D., Despr, J., Dishman, R. K., Franklin, B. A., & Garber, C. E. (1998). ACSM position stand: The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. *Medicine & Science in Sports & Exercise,* (6), 975. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsovi&AN=edsovi.00005768.199806000.00032&site=eds-live&scope=site

Prestes, J., De Lima, C., Frollini, A. B., Donatto, F. F., & Conte, M. (2009). Comparison of linear and reverse linear periodization effects on maximal strength and body composition. *Journal of Strength & Conditioning Research (Lippincott Williams & Wilkins), 23*(1), 266-274. doi:10.1519/JSC.0b013e3181874bf3

Ramírez-Vélez, R., La Rotta-Villamizar, D. R., Romero-García, J. A., Izquierdo, M., López-Albán, C. A., & Alonso-Martinez, A. (2016). Wingate anaerobic test percentile norms in colombian healthy adults. *Journal of Strength and Conditioning Research, 30*(1), 217-225. doi:10.1519/JSC.0000000000001054

Ramsbottom, R., Brewer, J., & Williams, C. (1988). A progressive shuttle run test to estimate maximal oxygen uptake. *British Journal of Sports Medicine, 22*(4), 141-144. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=3228681&site=eds-live&scope=site

Ratamess, N. A., Alvar, B. A., Evetoch, T. K., Housh, T. J., Kibler, W. B., Kraemer, W. J., & Triplett, N. T. (2009). Progression models in resistance training for healthy adults. *Medicine & Science in Sports & Exercise, 41*(3), 687-708. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=36871365&site=eds-live&scope=site

Ratamess, N. A., Faigenbaum, A. D., Mangine, G. T., Hoffman, J. R., & Kang, J. (2007). Acute muscular strength assessment using free weight bars of different thickness. *Journal of Strength & Conditioning Research (Allen Press Publishing Services Inc.), 21*(1), 240-244. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=24450269&site=eds-live&scope=site

Reilly, T., Morris, T., & Whyte, G. (2009). The specificity of training prescription and physiological assessment: A review. *Journal of Sports Sciences, 27*(6), 575-589. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=37579801&site=eds-live&scope=site

Rhea, M. R., Alvar, B. A., Burkett, L. N., & Ball, S. D. (2003). A meta-analysis to determine the dose response for strength development. *Medicine & Science in Sports & Exercise, 35*(3), 456-464. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=106784516&site=eds-live&scope=site

Ronnestad, B. R., Hansen, E. A., & Raastad, T. (2010). Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *European Journal of Applied Physiology,* (4), 965. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.230109824&site=eds-live&scope=site

Rowell, L. B. (1974). Human cardiovascular adjustments to exercise and thermal stress. *Physiological Reviews,* (54), 75-159. Retrieved from http://articles.sirc.ca/search.cfm?id=9172; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH9172&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=9172

Sahlin, K., Tonkonogi, M., & Söderlund, K. (1998). Energy supply and muscle fatigue in humans. *Acta Physiologica Scandinavica, 162*(3), 261-266. doi:10.1046/j.1365-201X.1998.0298f.x

Saltin, B. (1973). Metabolic fundamentals in exercise. *Medicine and Science in Sports, 5*(3), 137-146. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=4270581&site=eds-live&scope=site

Satoru, K., Kazumi, S., Shiro, T., Miho, M., Yoko, Y., Mihoko, A., . . . Hirohito, S. (2009). Cardiorespiratory fitness as a quantitative predictor of all-cause mortality and cardiovascular events in healthy men and women: A meta-analysis. *JAMA: The Journal of the American Medical Association,* (19), 2024. doi:10.1001/jama.2009.681

Sawka, M. N., Convertino, V. A., Eichner, E. R., Schnieder, S. M., & Young, A. J. (2000). Blood volume: Importance and adaptations to exercise training, environmental stresses, and trauma/sickness. *Medicine and Science in Sports and Exercise, 32*(2), 332-348. doi:10.1097/00005768-200002000-00012

Schoenfeld, B. (2011). The use of specialized training techniques to maximize muscle hypertrophy. *Strength & Conditioning Journal (Lippincott Williams & Wilkins), 33*(4), 60-65. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=65647211&site=eds-live&scope=site

Scott, W., Stevens, J., & Binder-Macleod, S. (2001). Human skeletal muscle fiber type classifications. *Physical Therapy, 81*(11), 1810-1816. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=6404833&site=eds-live&scope=site

Sedano, S., Marin, P. J., Cuadrado, G., & Redondo, J. C. (2013). Concurrent training in elite male runners: The influence of strength versus muscular endurance training on performance outcomes. *Journal of Strength and Conditioning Research,* (9), 2433. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.345880131&site=eds-live&scope=site

Selye, H. (1950). Stress and the general adaptation syndrome. *British Medical Journal, 1*(4667), 1383-1392. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=15426759&site=eds-live&scope=site

Skelly, L. E., Andrews, P. C., Gillen, J. B., Martin, B. J., Percival, M. E., & Gibala, M. J. (2014). High-intensity interval exercise induces 24-h energy expenditure similar to traditional endurance exercise despite reduced time commitment. *Applied Physiology, Nutrition & Metabolism, 39*(7), 845-848. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=96838583&site=eds-live&scope=site

Smith, M. M., Sommer, A. J., Starkoff, B. E., & Devor, S. T. (2013). *Crossfit-based high-intensity power training improves maximal aerobic fitness and body composition* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000326495200030&site=eds-live&scope=site

Sobrero, G., Arnett, S., Schafer, M., Stone, W., Lyons, S., Esslinger, K., . . . Maples, J. (2014). Crossfit vs. resistance-training: Effects of A six-week training program on selected performance indicators. *Medicine & Science in Sports & Exercise, 46*, 888. doi:10.1249/01.mss.0000496164.24306.23

Sproule, J., Kunalan, C., McNeill, M., & Wright, H. (1993). Validity of 20-MST for predicting VO2max of adult singaporean athletes. *British Journal of Sports Medicine, 27*(3), 202-204. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=8242281&site=eds-live&scope=site

Stankovic, D., Ignjatovic, M., Rakovic, A., Puletic, M., & Hodžic, S. (2014). The strength structure of sport climbers. / struktura snage sportskih penjaca. *Facta Universitatis: Series Physical Education & Sport, 12*(1), 11-18. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=96687946&site=eds-live&scope=site

Starritt, E. C., Angus, D., & Hargreaves, M. (1999). Effect of short-term training on mitochondrial ATP production rate in human skeletal muscle. *Journal of Applied Physiology, 86*(2), 450-454. doi:10.1152/jappl.1999.86.2.450

Stathokostas, L., Jacob-Johnson, S., Petrella, R. J., & Paterson, D. H. (2004). Longitudinal changes in aerobic power in older men and women. *Journal of Applied Physiology, 97*(2), 781-789. doi:10.1152/japplphysiol.00447.2003

Stickland, M. K., Petersen, S. R., & Bouffard, M. (2003). Prediction of maximal aerobic power from the 20-m multi-stage shuttle run test. *Canadian Journal of Applied Physiology, 28*(2), 272-282. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=9633357&site=eds-live&scope=site

Stone, M. H., Keith, R. E., Kearney, J. T., Fleck, S. J., Wilson, G. D., & Triplett, N. T. (1991). Overtraining: A review of the signs, symptoms and possible causes. *Journal of Applied Sport Science Research, 5*(1), 35-50. Retrieved from http://articles.sirc.ca/search.cfm?id=280642; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH280642&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=280642

Stone, M. H., Stone, M. E., Sands, W. A., Pierce, K. C., Newton, R. U., Haff, G. G., & Carlock, J. (2006). Maximum strength and strength training -- A relationship to endurance? *Strength & Conditioning Journal (Allen Press), 28*(3), 44-53. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=21353390&site=eds-live&scope=site

Stone, M. H., Stone, M., & Sands, B. (2007). *Principles and practice of resistance training* Champaign, IL : Human Kinetics, c2007. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat03710a&AN=alb.3946483&site=eds-live&scope=site

Tanaka, H., & Swensen, T. (1998). Impact of resistance training on endurance performance: A new form of cross-training? *Sports Medicine, 25*(3), 191-200. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=9593802&site=eds-live&scope=site

Tang, K., Xia, F. C., Wagner, P. D., & Breen, E. C. (2010). Exercise-induced VEGF transcriptional activation in brain, lung and skeletal muscle. *Respiratory Physiology & Neurobiology, 170*, 16-22. doi:10.1016/j.resp.2009.10.007

Taylor, A. W. (1973). Effects of exercise and training on the activities of human skeletal muscle glycogen cycle enzymes. () Retrieved from http://articles.sirc.ca/search.cfm?id=18554; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH18554&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=18554

Tihanyi, J., Apor, P., & Fekete, G. (1982). Force-velocity-power characteristics and fiber composition in human knee extensor muscles. *European Journal of Applied Physiology & Occupational Physiology, 48*(3), 331. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=73050485&site=eds-live&scope=site

Tohmiya, S., Yoshida, S., Kikuchi, N., & Nakazato, K. (2015). Effect of concurrent strength and low-intensity endurance training on same day versus day after. *Advances in Exercise & Sports Physiology, 21*(4), 97-97. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=112021920&site=eds-live&scope=site

Urhausen, A., & Kindermann, W. (2002). Diagnosis of overtraining: What tools do we have? *Sports Medicine, 32*(2), 95-102. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=6067116&site=eds-live&scope=site

Uusltalo, A. L. T. (2001). Overtraining : Making a difficult diagnosis and implementing targeted treatment. *Physician and Sportsmedicine, 29*(5), 35-50. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edscal&AN=edscal.1058437&site=eds-live&scope=site

van Borselen, F., Vos, N. H., Fry, A. C., & Kraemer, W. J. (1992). Exercise physiology corner: The role of anaerobic exercise in overtraining. *National Strength and Conditioning Association Journal, 14*(3), 74-78. doi:10.1519/0744-0049(1992)0142.3.CO;2

Wall, C. B., Starek, J. E., Fleck, S. J., & Byrnes, W. C. (2004). Prediction of indoor climbing performance in women rock climbers. *Journal of Strength & Conditioning Research (Allen Press Publishing Services Inc.), 18*(1), 77-83. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=106772437&site=eds-live&scope=site

Waryasz, G. R., Daniels, A. H., Gil, J. A., Suric, V., & Eberson, C. P. (2016). Personal trainer demographics, current practice trends and common trainee injuries. *Orthopedic Reviews, 8*(3), 98-105. doi:10.4081/or.2016.6600

Watts, P. B., Martin, D. T., & Durtschi, S. (1993). Anthropometric profiles of elite male and female competitive sport rock climbers. *Journal of Sports Sciences, 11*(2), 113-117. Retrieved from http://articles.sirc.ca/search.cfm?id=377305; http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=SPH377305&site=eds-live&scope=site; http://articles.sirc.ca/search.cfm?id=377305

Weakley, J. J. S., Till, K., Darrall-Jones, J., Roe, G. A. B., Phibbs, P. J., Read, D. B., & Jones, B. L. (2017). The influence of resistance training experience on the between-day reliability of commonly used strength measures in male youth athletes. *Journal of Strength and Conditioning Research, 31*(7), 2005-2010. doi:10.1519/JSC.0000000000001883

Weston, M., Taylor, K., Batterham, A., & Hopkins, W. (2014). Effects of low-volume high-intensity interval training (HIT) on fitness in adults: A meta-analysis of controlled and non-controlled trials. *Sports Medicine, 44*(7), 1005-1017. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=96797298&site=eds-live&scope=site

What is CrossFit?

Widrick, J. J., Stelzer, J. E., Shoepe, T. C., & Garner, D. P. (2002). Functional properties of human muscle fibers after short-term resistance exercise training. *American Journal of Physiology - Regulatory Integrative and Comparative Physiology, 283*(52-2), R408-R416. Retrieved from

http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0036340716&site=eds-live&scope=site

Wilson, G., Newton, R. U., Murphy, A. J., & Humphries, B. J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise, 25*(11), 1279-1286. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0027368556&site=eds-live&scope=site

Wilson, J., Anderson, J., Wilson, S., Marin, P., Rhea, M., & Loenneke, J. (2012). *Concurrent training: A meta-analysis examining interference of aerobic and resistance exercises* Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000306858000035&site=eds-live&scope=site

Wilson, J., Loenneke, J., Jo, E., Zourdos, M., Kim, J., & Wilson, G. (2012). The effects of endurance, strength, and power training on muscle fiber type shifting. *Journal of Strength and Conditioning Research, 26*(6), 1724-1729. doi:10.1519/JSC.0b013e318234eb6f

Yakovlev, N. N. (1975). Biochemistry of sport in the soviet union: Beginning, development, and present status. *Medicine and Science in Sports, 7*(4), 237-247. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=1235148&site=eds-live&scope=site

Yates, J., & Kamon, E. (1983). A comparison of peak and constant angle torque-velocity curves in fast and slow-twitch populations. *European Journal of Applied Physiology &*

Occupational Physiology, 51(1), 67. Retrieved from http://login.ezproxy.library.ualberta.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=73050797&site=eds-live&scope=site

Ydfors, M., Fischer, H., Mascher, H., Blomstrand, E., Norrbom, J., & Gustafsson, T. (2013). The truncated splice variants, NT-PGC-1a and PGC-1a4, increase with both endurance and resistance exercise in human skeletal muscle. *Physiological Reports, 1*(6), e00140-e00140. doi:10.1002/phy2.140

Zagdsuren, B., Evans, G. S., Inman, C., Stone, W., Arnett, S., Schafer, M., . . . Callahan, Z. (2015). Crossfit vs. circuit-training: Effects of A ten-week training program on aerobic, anaerobic and flexibility indicators.: 2924 board #239 may 29, 3: 30 PM - 5: 00 PM. *Medicine & Science in Sports & Exercise,* (5), 801. doi:10.1249/01.mss.0000478926.16823.b9

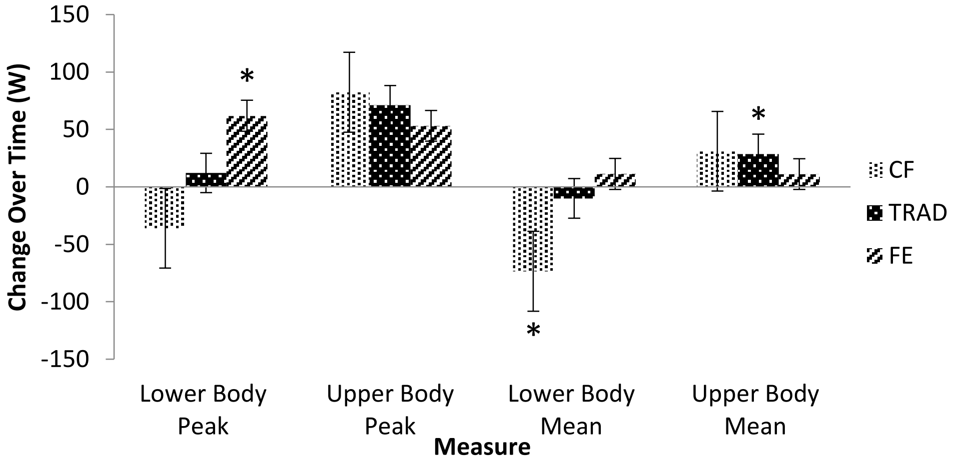


***Figure 1A**. Within group comparison: difference between baseline vs. post-training values of power output. Peak power was measured as the highest average 5-second power output during a 30 second Wingate test; mean power was measured as the highest average power output of an entire (i.e. 30 second) Wingate test. All lower body Wingate testing was performed using a standardized cycle ergometer; all upper body Wingate testing was performed using a standardized arm crank ergometer. * = Paired Samples T-test (baseline vs. post-training power output) $p < 0.05$; W = Watts.*

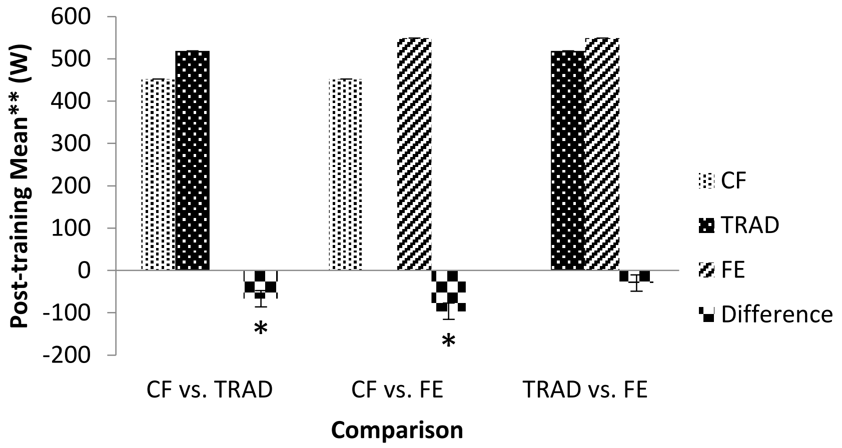


***Figure 1B**. Between group comparison: difference in post-training Lower Body Mean Power Output values. All values were calculated using data recorded during lower body Wingate testing. * = One-way ANCOVA $p < 0.05$; W = Watts. ** = Adjusted for between group differences in pre-training means (as the covariate).*

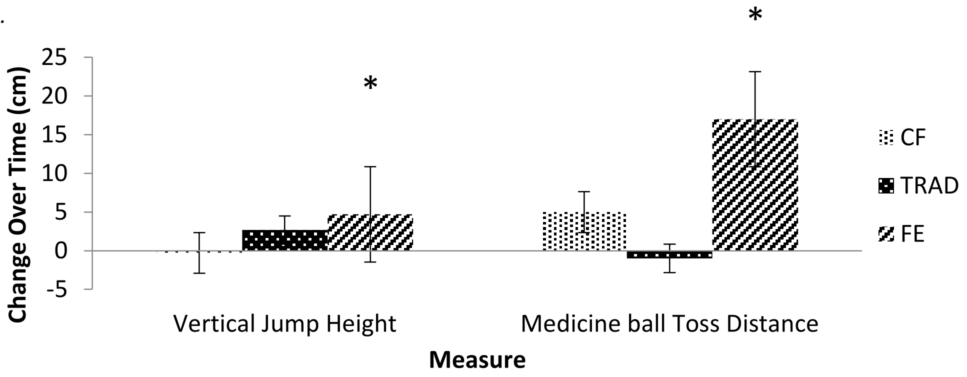


***Figure 1C.** Within group comparison: difference between baseline vs. post-training values of instantaneous power. Lower body instantaneous power was measured using a vertical jump test (i.e. distance between standing reach height and top of maximal effort jump); upper body instantaneous power was measured using a seated medicine ball (8lb) throw test; the resulting vertical and horizontal displacement values from each test (respectively) are displayed in centimeters in the above figure. * = Paired Samples T-test (baseline vs. post-training fatigue index) $p < 0.05$.*

***Figure 1.** Anaerobic Fitness Response to Different Modalities of Resistance Training*

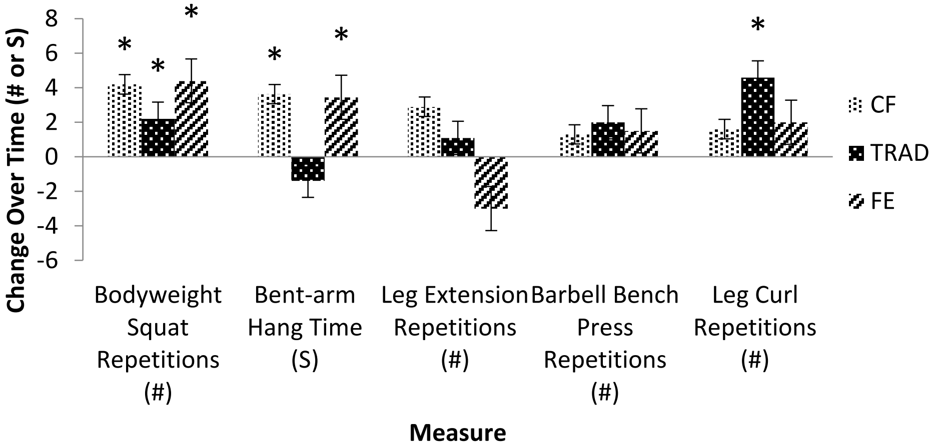


***Figure 2A**. Within group comparison: difference between baseline vs. post-training values in all measures used to assess muscle endurance. Leg extension, barbell bench press, and leg curl exercises were performed to failure training using 50% of the baseline estimated 1-RM for each respective exercise at a pace of 30 repetitions (60 beats) per minute; the maximum number of repetitions performed using this protocol are reported as numbers (#) in the above figure. Bodyweight squats were performed as quickly as possible to a fixed height (an 8lb slam ball); the maximum number of repetitions (performed in 60 seconds) using this protocol are also reported as numbers (#) in the above figure. The bent-arm hang exercise was held continuously, in a single repetition to failure; consequently, the measurement metric for this test is displayed as time (seconds) in the above figure. * = Paired Samples T-test (baseline vs. post-training muscular endurance) p < 0.05; # = number of repetitions; S = seconds.*

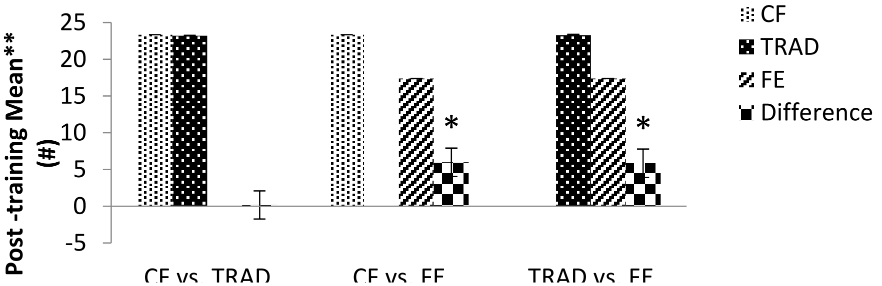


***Figure 2C**. Between group comparison: difference in post-training Leg Extension Repetitions (to failure). * = One-way ANCOVA p < 0.05; # = number of repetitions. ** = Adjusted for between group differences in pre-training means (as the covariate).*

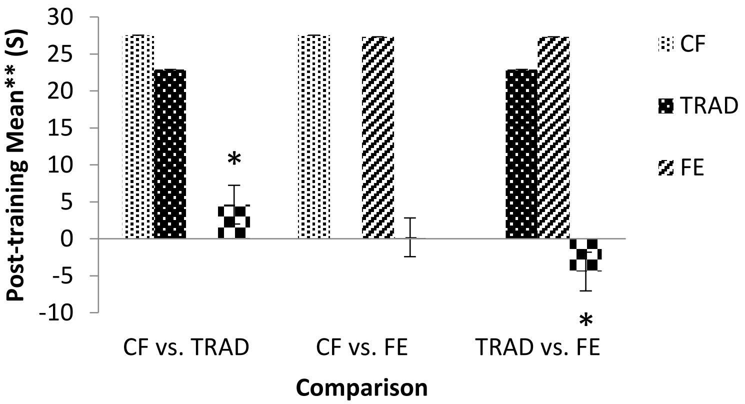


***Figure 2B**. Between group comparison: difference in post-training Bent-arm Hang Time to (failure). * = One-way ANCOVA p < 0.05; S = seconds. ** = Adjusted for between group differences in pre-training means (as the covariate).*

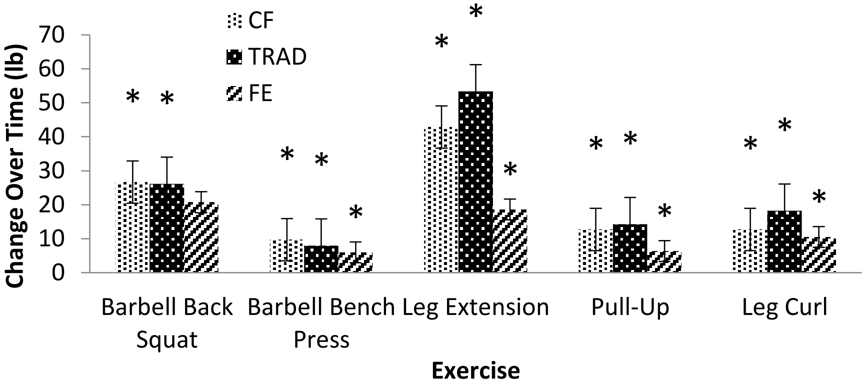


***Figure 2D**. Within group comparison: difference between baseline vs. post-training E1-RM (estimated 1-repetition maximum) values in all exercises used to assess muscle strength. E1-RM values are reported in pounds (lb) in the above figure. * = Paired Samples T-test (baseline vs. post-training E1-RM) p < 0.05.*

***Figure 2.** Skeletal Muscle Response to Different Modalities of Resistance Training*

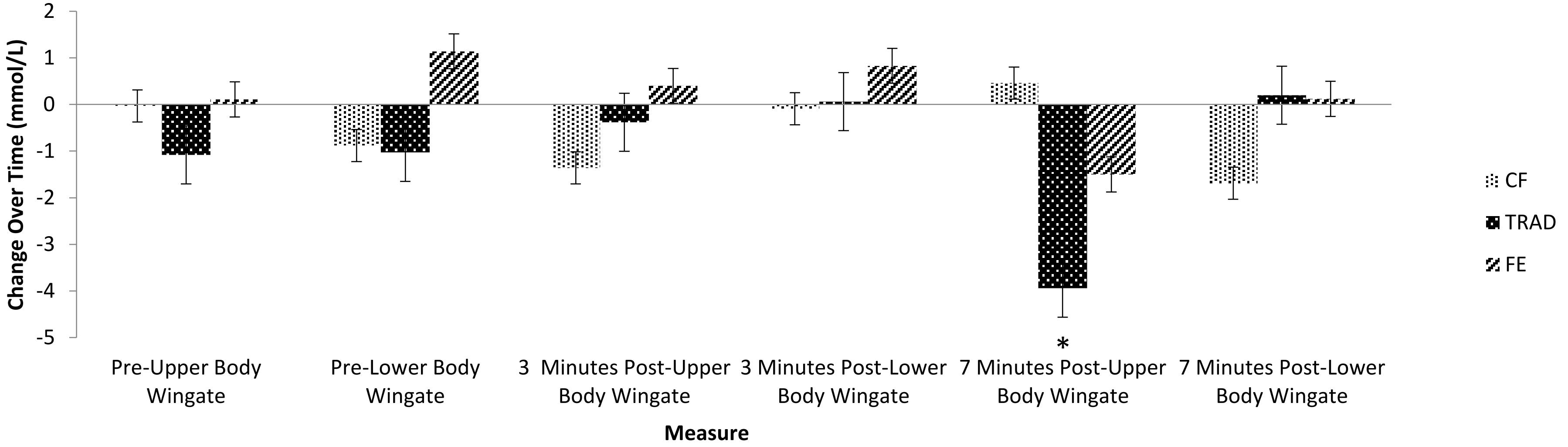


Figure 3A: Within group comparison: *difference between baseline vs. post-training measures of blood lactate. Blood lactate was measured before, 3 minutes-post, and 7 minutes-post upper and lower body Wingate tests. The resulting blood lactate values are displayed in the above figure in mmol/L.* = Paired Samples T-test (baseline vs. post-training fatigue index) $p < 0.05$.*

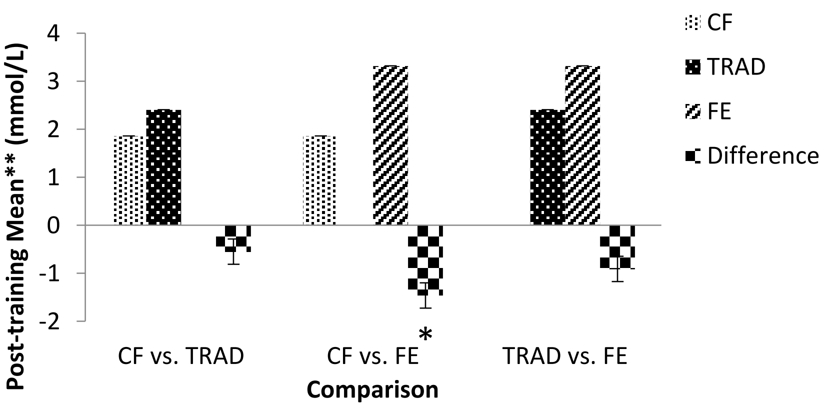


***Figure 3B**. Between group comparison: difference in post-training pre-Lower Body Wingate values. * = One-way ANCOVA $p < 0.05$. ** = Adjusted for between group differences in pre-training means (as the covariate).*

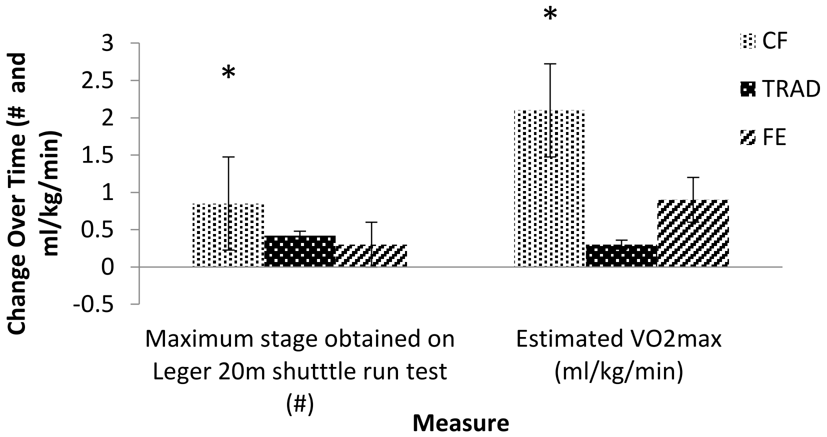


Figure 3C: Within group comparison: *difference between baseline vs. post-training measures of aerobic fitness. The highest full stage (i.e. 1,2,3, etc.) obtained during the 20 meter shuttle run test is displayed in the above figure as numbers (#). These stages were converted into estimated VO_{2max} values using the formula provided in the original article published on Leger 20-m shuttle run test (Leger et al., 1988); the resultant estimated VO_{2max} values in the above figure are displayed in ml/kg/min.* = Paired Samples T-test (baseline vs. post-training fatigue index) $p < 0.05$.*

<u>Figure 3.</u> *<u>Energy Metabolism and Aerobic Fitness Response to Different Modalities of Resistance Training</u>*

Table 1: Pictorial Summary of Significant Results

Section	Test	Baseline vs. post-training (i.e. main effects for time) (<.05)			Difference in Post-training Mean** (i.e. main effects for group) (<.05)		
		CF	**TRAD**	**FE**	**CF vs. TRAD**	**CF vs. FE**	**TRAD vs. FE**
Descriptive Information	Bodyweight (kg)						
	Time Performing Moderate Intensity Exercise (minutes)						
	Time Performing Vigorous Intensity Exercise (minutes)						
	Total Time Exercising During Study (minutes)						
Energy Metabolism during Rest and After Exercise	Pre-Upper Body Wingate Blood Lactate						
	3 Minutes Post-Upper Body Wingate Blood Lactate						
	7 Minutes Post-Upper Body Wingate Blood Lactate		↓ 3.94 ± 1.47 mmol/l				
	Pre-Lower Body Wingate Blood Lactate					**CF** < **FE** (by 1.46 ± 0.56 mmol/L)	
	3 Minutes Post-Lower Body Wingate Blood Lactate						

	7 Minutes Post-Lower Body Wingate Blood Lactate					
Upper Body Anaerobic Power	Upper Body Peak Power Output					
	Medicine Ball Toss Distance			↑ 0.17 ± 0.07 m		
Upper Body Anaerobic Capacity	Upper Body Mean Power Output		↑ 28.47 ± 9.00 watts			
	Upper Body Fatigue Index					
Lower Body Anaerobic Power	Lower Body Peak Power Output			↑ 61.81 ± 20.87 watts		
	Vertical Jump Height			↑ 4.70 ± 1.89 cm		
Lower Body Anaerobic Capacity	Lower Body Mean Power Output*	↓ 73.43 ± 22.84 watts			**CF < TRAD** (by 66.71 ± 28.09 watts)	**CF < FE** (by 96.36 ± 30.98 watts)
	Lower Body Wingate Fatigue Index*			↑ 4.85 ± 1.62%		
Aerobic Capacity	Maximum Score Obtained on the 20 meter Shuttle Run Test	↑ 0.85 ± 0.22 stages				
	Estimated VO2max	↑ 2.10 ± 0.78 ml/kg/min				
Musculoskeletal Strength	Barbell Back Squat Estimated 1 Repetition Maximum	↑ 26.63 ± 9.08 lb	↑ 26.07 ± 8.87 lb			

	Barbell Bench Press Estimated 1 Repetition Maximum	↑ 9.67 ± 3.15 lb	↑ 7.96 ± 3.12 lb	↑ 5.96 ± 1.36 lb			
	Leg Extension Estimated 1 Repetition Maximum	↑ 42.82 ± 11.68 lb	↑ 53.32 ± 12.17 lb	↑ 18.59 ± 7.66 lb			
	Pull-up Estimated 1 Repetition Maximum	↑ 12.73 ± 3.35 lb	↑ 14.23 ± 3.89 lb	↑ 6.35 ± 2.49 lb			
	Leg Curl Estimated 1 Repetition Maximum	↑ 12.57 ± 3.57 lb	↑ 18.16 ± 3.15 lb	↑ 10.51 ± 2.56 lb			
Musculoskeletal Endurance	Maximum Bodyweight Squat Repetitions Obtained in 1 Minute	↑ 4.20 ± 1.42 reps	↑ 2.20 ± 0.70 reps	↑ 4.40 ± 1.58 reps			
	Bent-arm Hang Time to Failure	↑ 3.62 ± 0.89 seconds		↑ 3.45 ± 1.46 seconds	**CF > TRAD** (by 4.63 ± 1.95 seconds)		**TRAD < FE** (by 4.42 ± 1.96 seconds)
	Leg Extension Repetitions to Failure at 50% Estimated 1 Repetition Maximum					**CF > FE** (by 5.96 ± 2.10 reps)	**TRAD > FE** (by 5.83 ± 2.30 reps)
	Barbell Bench Press Repetitions to Failure at 50% Estimated 1 Repetition Maximum						
	Leg Curl Repetitions to Failure at 50% Estimated 1 Repetition Maximum		↑ 4.60 ± 1.23 reps				

* Baseline values significantly different between groups (p < .05); see Appendix E for specific group means. Only values that reached significance are displayed in the above table: ↑ = significant increase (relative to baseline, p < .05); ↓ = significant decrease (relative to baseline, p < .05); Group 1 > Group 2 = the post-training mean in group 1 was significantly greater than the post-training mean in group 2 (p < .05); *** = adjusted for between group differences in pre-training means (as the covariate).*

Table 2: Crossfit Manual Exercise Modality Definitions and Example Exercises

	Modality		
	Gymnastics	**Metabolic Conditioning**	**Weightlifting**
Definition	The gymnastics modality comprises body-weight exercises/elements or calisthenics, and its primary purpose is to improve body control by improving neurological components such as coordination, balance, agility, and accuracy, and to improve functional upper-body capacity and trunk strength.	The monostructural metabolic conditioning activities are commonly referred to as "cardio," the purpose of which is primarily to improve cardiorespiratory capacity and stamina. They are repetitive, cyclical movements that could be sustained for long periods of time.	The weightlifting modality comprises the most important weight-training basics, Olympic lifts and powerlifting, where the aim is primarily to increase strength, power, and hip/leg capacity. This category includes any exercise with the addition of an external load.
Example Exercises	Air-Squat Pull-up Push-up Dip Handstand Push-up Rope Climb Muscle-up Press to Handstand Back Extension Sit-up Jump Lunge	Run Bike Row Jump Rope	Deadlift Cleans Press Snatch Clean and Jerk Medicine-Ball Drills Kettlebell Swings

Note – the information in this table was taken, in its entirety, from the official CrossFit Training Guide (Glassman, 2010)

Table 3: The 20 meter shuttle run test: predictions of VO2max from maximal shuttle run speed – adapted from Lèger et al. (1988)

Stage (min)	**Speed (km/h)**	**Predicted VO2max (ml/kg/min)**
1	8.5	23.6
2	9.0	26.6
3	9.5	29.6
4	10.0	32.6
5	10.5	35.6
6	11.0	38.6
7	11.5	41.6
8	12.0	44.6
9	12.5	47.6
10	13.0	50.6
11	13.5	53.6
12	14.0	56.6
13	14.5	59.6
14	15.0	62.6
15	15.5	65.6
16	16.0	68.6
17	16.5	71.6
18	17.0	74.6
19	17.5	77.6
20	18.0	80.6

Table 4: Number of Participant Increases and Decreases in Variables that Differed Significantly Over Time

		Wingate Peak and Mean Power Outputs		
		Lower Body Wingate Peak Power (Watts)		
		CF	**TRAD**	**FE**
Increase Over Time	**Number of Participants (N)**	4	7	9
Decrease Over Time	**N**	6	3	1
		Lower Body Wingate Mean Power (Watts)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	1	4	5
Decrease Over Time	**N**	9	6	5
		Upper Body Wingate Mean Power (Watts)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	7	8	5
Decrease Over Time	**N**	3	2	5
		Energy Metabolism		
		Blood Lactate Concentration - 7 Minutes Post Upper Body Wingate Test (mmol/L)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	6	2	2
Decrease Over Time	**N**	4	8	8
		Aerobic Fitness		
		Maximum Stage Obtained During 20 Meter Shuttle Run Test		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	7	7	7
Decrease Over Time	**N**	1	2	2
		Estimated VO_{2max} (ml/kg/min)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	7	3	4
Decrease Over Time	**N**	1	2	1
		Muscular Strength: Estimated 1-RMs		
		Barbell Back Squat (lb)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	9	8	7
Decrease Over Time	**N**	1	1	0
		Barbell Bench Press (lb)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	8	8	9
Decrease Over Time	**N**	1	0	0
		Leg Extension (lb)		
		CF	**TRAD**	**FE**
Increase Over Time	**N**	9	9	8

Decrease Over Time	**N**	0	1	2
			Pull-up (lb)	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	10	8	7
Decrease Over Time	**N**	0	2	3
			Leg Curl (lb)	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	7	9	8
Decrease Over Time	**N**	1	0	0
		Muscular Endurance		
			Maximum Bodyweight Squat Repetitions Performed in 1 Minute	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	8	7	8
Decrease Over Time	**N**	2	1	2
			Maximum Bent-arm Hang Time (Performed to Failure)	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	8	6	7
Decrease Over Time	**N**	1	4	2
			Maximum Leg Curl Repetitions (Performed to Failure at 50% of Estimated Leg Curl 1-RM)	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	5	8	6
Decrease Over Time	**N**	4	1	3
		Instantaneous Power		
			Vertical Jump Height (cm)	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	5	4	9
Decrease Over Time	**N**	4	4	1
			8lb Medicine Ball Seated Toss Distance (m)	
		CF	**TRAD**	**FE**
Increase Over Time	**N**	6	3	7
Decrease Over Time	**N**	4	6	3

Appendix A: Descriptive Information

Table A1: Pre-training Participant Data

Group	Age (Years)	Gender		Pre-training Bodyweight (Kg)	History of Consistent Exercise (Years)			Pre-Study Exercise Frequency (Days/Week)			Pre-Study Crossfit Experience	
		Male	Female		0.5 - 1	1 - 2	>2	1-2	2-3	>3	Never	A Few Times
CF	24.5 ± 1.01	5	5	73.61 ± 3.09	1	4	5	2	4	4	7	3
TRAD	23.50 ± 1.10	5	5	69.92 ± 3.09	2	1	7	0	4	6	6	4
FE	21.60 ± 0.81	5	5	66.37 ± 3.09	3	1	6	1	3	6	9	1

***Note**: All measures (other than bodyweight) were based on subjective answers to questions; all participant responses were collected during the first day of baseline testing (prior to training initiation).*

Table A2: Post-training Participant Data

Group	Post-training Bodyweight (Kg)	Number of Supervised Training Sessions Attended	Days Between First Pre-training and Last Post-training Tests	Total Time Exercising During Study (minutes)*	Time Performing Moderate Intensity Exercise (minutes)†	Time Performing Vigorous Intensity Exercise (minutes) ‡
CF	74.00 ± 3.09	15.00 ± 0.26	49.30 ± 1.78	2606.40 ± 1186.33	773.00 ± 389.60	1833.40 ± 826.68
TRAD	70.65 ± 3.09	16.00 ± 0.49	49.20 ± 3.82	1408.50 ± 158.26	446.30 ± 120.31	962.20 ± 106.78
FE	66.48 ± 3.09	0	49.80 ± 2.62	1978.50 ± 188.14	546.00 ± 122.44	1432.50 ± 215.56

***Note**: All measures (other than bodyweight) were based on subjective responses from each participant (logged in daily or weekly training surveys; these can be found in Appendix C); *includes exercise performed both during supervised training hours and outside of supervised sessions; †includes any form of exercise in which participants felt they were working at a RPE of 4-6/10; ‡ includes any form of exercise in which participants felt they were working at a RPE of 7-10/10.*

Appendix B: Descriptive Data – Within and Between Group Comparisons

			Within Group Comparisons (Pre- vs. Post-training)						Between Group Comparisons (Difference in Post-training Mean**)						
Section	**Test**	**Group**	**Time**	**Mean**	**Difference**	**T**	**p**	**95% CI**	**Post-training Mean****	**CF vs.**	**p**	**95% CI**	**TRAD vs.**	**p**	**95% CI**
Descriptive Information	**Bodyweight (kg)**	**CF**	Pre	73.61 ± 3.09	0.39 ± 0.39	(9) = 0.99	.346	-0.50, 1.27	70.38 ± 0.46						
			Post	74.00 ± 3.09											
		TRAD	Pre	69.92 ± 3.09	0.74 ± 0.39	(9) = -0.06	.090	-0.14, 1.61	70.70 ± 0.45	-0.31 ± 0.65	.632	-1.64, 1.01			
			Post	70.65 ± 3.09											
		FE	Pre	66.37 ± 3.09	0.11 ± 0.53	(9) = 0.21	.836	-1.09, 1.32	70.04 ± 0.46	0.34 ± 0.67	.611	-1.03, 1.72	0.66 ± 0.64	.318	-0.77, 1.98
			Post	66.48 ± 3.09											
	Time Performing Moderate Intensity Exercise (minutes)	**CF**		773.00 ± 389.60											
		TRAD		446.30 ± 120.31											
		FE		546.00 ± 122.44											
	Time Performing Vigorous Intensity Exercise (minutes)	**CF**		1833.40 ± 826.68											
		TRAD		962.20 ± 106.78											
		FE		1432.50 ± 215.56											
	Total Time Exercising During Study (minutes)	**CF**		2606.40 ± 1186.33											
		TRAD		1408.50 ± 158.26											

FE	1978.50 ± 188.14

**Indicates statistical significance (p<0.05); CF = Crossfit training intervention; TRAD = Traditional training intervention; FE = Free Exercise training intervention; ** = adjusted for between group differences in pre-training means (as the covariate); CI = Confidence Interval.*

Appendix C: Energy Metabolism Data – Within and Between Group Comparisons

			Within Group Comparisons (Pre- vs. Post-training)						Between Group Comparisons (Difference in Post-training Mean**)						
Section	**Test**	**Group**	**Time**	**Mean**	**Difference**	**T**	**p**	**95% CI**	**Post-training Mean****	**CF vs.**	**p**	**95% CI**	**TRAD vs.**	**p**	**95% CI**
Blood Lactate - Upper Body Wingate	**Pre-Test (mmol/L)**	**CF**	Pre	1.97 ± 0.54	-0.03 ± 0.47	(9) = -0.06	.950	-1.09. 1.03	2.24 ± 0.40						
			Post	1.94 ± 0.47											
		TRAD	Pre	2.95 ± 0.54	-1.08 ± 0.57	(9) = -1.89	.092	-2.38, 0.22	1.69 ± 0.40						
			Post	1.87 ± 0.47											
		FE	Pre	2.83 ± 0.54	0.11 ± 0.37	(9) = 0.30	.771	-0.72, 0.94	2.82 ± 0.40						
			Post	2.94 ± 0.47											
	3 Minutes Post-Test (mmol/L)	**CF**	Pre	12.08 ± 1.04	-1.36 ± 1.71	(9) = -0.79	.448	-5.24, 2.52	10.44 ± 1.03						
			Post	10.72 ± 1.00											
		TRAD	Pre	10.16 ± 1.04	-0.38 ± 0.96	(9) = -0.40	.700	-2.54, 1.78	9.89 ± 1.00						
			Post	9.78 ± 1.00											
		FE	Pre	9.49 ± 1.04	0.40 ± 1.07	(9) = 0.37	.718	-2.03, 2.83	10.09 ± 1.01						
			Post	9.89 ± 1.00											
	7 Minutes Post-Test (mmol/L)	**CF**	Pre	7.88 ± 1.15	0.46 ± 1.05	(9) = 0.44	.671	-1.91, 2.83	9.09 ± 0.91						
			Post	8.34 ± 0.94											
		TRAD	Pre	11.99 ± 1.15	**-3.94 ± 1.47***	**(9) = -2.68**	**.025**	**-7.27, -0.61**	7.31 ± 0.91						
			Post	8.05 ± 0.94											
		FE	Pre	9.97 ± 1.15	-1.50 ± 0.71	(9) = -2.11	.064	-3.11, 0.11	8.46 ± 0.86						
			Post	8.47 ± 0.94											

Blood Lactate - Lower Body Wingate	**Pre-Test (mmol/L)**	**CF**	Pre	2.73 ± 0.74	-0.88 ± 0.40	(9) = -2.21	.055	-1.78, 0.02	1.86 ± 0.40						
			Post	1.85 ± 0.40											
		TRAD	Pre	3.51 ± 0.74	-1.03 ± 1.15	(9) = -0.90	.394	-3.63, 1.57	2.41 ± 0.40	-0.55 ± 0.57	.339	-1.71, 0.61			
			Post	2.48 ± 0.40											
		FE	Pre	2.11 ± 0.74	1.14 ± 0.55	(9) = 2.07	.068	-0.10, 2.38	3.32 ± 0.40	**-1.46 ± 0.56***	**.015**	**-2.62, -0.31**	-0.91 ± 0.58	.126	-2.10, 0.27
			Post	3.25 ± 0.40											
	3 Minutes Post-Test (mmol/L)	**CF**	Pre	11.78 ± 0.84	-0.09 ± 0.88	(9) = 0.10	.921	-2.08, 1.90	11.62 ± 1.03						
			Post	11.69 ± 0.98											
		TRAD	Pre	13.06 ± 0.84	0.06 ± 1.45	(9) = 0.04	.968	-3.22, 3.34	13.13 ± 1.00						
			Post	13.12 ± 0.98											
		FE	Pre	13.73 ± 0.84	0.83 ± 1.55	(9) = 0.54	.605	-2.67, 4.33	14.62 ± 1.02						
			Post	14.56 ± 0.98											
	7 Minutes Post-Test (mmol/L)	**CF**	Pre	12.17 ± 0.77	-1.69 ± 0.79	(9) = -2.14	.061	-3.47, 0.09	10.65 ± 0.79						
			Post	10.48 ± 0.88											
		TRAD	Pre	11.79 ± 0.77	0.20 ± 1.06	(9) = 0.19	.854	-2.19, 2.59	12.37 ± 0.80						
			Post	11.99 ± 0.88											
		FE	Pre	13.46 ± 0.77	0.12 ± 0.65	(9) = 0.19	.857	-1.34, 1.58	13.04 ± 0.81						
			Post	13.58 ± 0.88											

**Indicates statistical significance (p<0.05); CF = Crossfit training intervention; TRAD = Traditional training intervention; FE = Free Exercise training intervention; ** = adjusted for between group differences in pre-training means (as the covariate); CI = Confidence Interval.*

Appendix D: Anaerobic Fitness Data – Within and Between Group Comparisons

			Within Group Comparisons (Pre- vs. Post-training)						Between Group Comparisons (Difference in Post-training Mean**)						
Section	**Test**	**Group**	**Time**	**Mean**	**Difference**	**T**	**p**	**95% CI**	**Post-training Mean****	**CF vs.**	**p**	**95% CI**	**TRAD vs.**	**p**	**95% CI**
Upper Body Anaerobic Power	**Peak Power Output (W)**	**CF**	Pre	484.02 ± 61.34	82.37 ± 41.83	(9) = 1.97	.080	-12.27, 177.00	550.35 ± 29.17						
			Post	566.39 ± 47.13											
		TRAD	Pre	450.31 ± 61.34	71.11 ± 34.60	(9) = 2.06	.070	-7.17, 149.39	526.00 ± 29.08						
			Post	521.42 ± 47.13											
		FE	Pre	439.06 ± 61.34	53.11 ± 34.60	(9) = 1.53	.159	-25.17, 131.39	503.63 ± 29.12						
			Post	492.17 ± 47.13											
	Medicine Ball Toss (m)	**CF**	Pre	4.11 ± 0.29	0.05 ± 0.14	(9) = 0.37	.720	-0.26, -0.36	4.05 ± 0.11						
			Post	4.16 ± 0.29											
		TRAD	Pre	4.04 ± 0.29	-0.01 ± 0.11	(9) = -0.10	.925	-0.27, 0.25	3.99 ± 0.11						
			Post	4.03 ± 0.29											
		FE	Pre	3.83 ± 0.29	**0.17 ± 0.07***	**(9) = 2.38**	**.041**	**0.01, 0.34**	4.16 ± 0.11						
			Post	4.00 ± 0.29											
Upper Body Anaerobic Capacity	**Mean Wingate Power Output (W)**	**CF**	Pre	253.05 ± 36.34	30.93 ± 15.97	(9) = 1.94	.085	-5.21, 67.07	274.48 ± 12.16						
			Post	283.98 ± 33.39											
		TRAD	Pre	263.95 ± 36.34	**28.74 ± 9.00***	**(9) = 3.19**	**.011**	**8.38, 49.09**	273.83 ± 12.22						
			Post	292.69 ± 33.39											
		FE	Pre	208.94 ± 36.34	11.10 ± 13.00	(9) = 0.85	.415	-18.30, 40.50	248.40 ± 12.32						
			Post	220.04 ± 33.39											

Lower Body Anaerobic Power	**Peak Power (W)**	**CF**	Pre	778.57 ± 61.47	-36.02 ± 32.07	(9) = -1.12	.290	-108.56, 36.52	704.84 ± 26.46						
			Post	742.55 ± 65.41											
		TRAD	Pre	737.54 ± 61.47	12.12 ± 23.13	(9) = 0.52	.613	-40.21, 64.45	752.08 ± 26.27						
			Post	749.66 ± 65.41											
		FE	Pre	703.92 ± 61.47	**61.81 ± 20.87***	**(9) = 2.62**	**.016**	**14.60, 109.02**	801.02 ± 26.44						
			Post	765.73 ± 65.41											
	Vertical Jump (cm)	**CF**	Pre	45.75 ± 3.91	-0.28 ± 0.95	(9) = -0.30	.774	-2.42, 1.86	46.71 ± 1.95						
			Post	45.47 ± 3.99											
		TRAD	Pre	44.58 ± 3.91	2.67 ± 2.63	(9) = 1.02	.336	-3.27, 8.61	49.53 ± 1.96						
			Post	47.24 ± 3.99											
		FE	Pre	51.05 ± 3.91	**4.70 ± 1.89***	**(9) = 2.48**	**.035**	**0.42, 8.98**	52.22 ± 1.98						
			Post	55.75 ± 3.99											
Lower Body Anaerobic Capacity	**Mean Power (W)**	**CF**	Pre	586.92 ± 36.33	**-73.43 ± 22.84***	**(9) = -3.22**	**.011**	**-125.09, -21.77**	452.42 ± 20.52						
			Post	513.49 ± 43.91											
		TRAD	Pre	549.29 ± 36.22	-10.06 ± 16.23	(9) = -0.62	.551	-46.78, 26.66	519.13 ± 19.76	**-66.71 ± 28.09***	**.025**	**-124.45, -8.97**			
			Post	539. 23 ± 43.91											
		FE	Pre	456.28 ± 36.22	11.34 ± 19.06	(9) = 0.59	.567	-31.79, 54.47	548.79 ± 21.15	**-96.36 ± 30.98***	**.004**	**-160.05, -32.68**	-29.65 ± 29.46	.323	-90.22, 30.91
			Post	467.62 ± 43.91											

**Indicates statistical significance (p<0.05); CF = Crossfit training intervention; TRAD = Traditional training intervention; FE = Free Exercise training intervention; ** = adjusted for between group differences in pre-training means (as the covariate); CI = Confidence Interval.*

Appendix E: Aerobic Fitness Data – Within and Between Group Comparisons

			Within Group Comparisons (Pre- vs. Post-training)						Between Group Comparisons (Difference in Post-training Mean**)						
Section	**Test**	**Group**	**Time**	**Mean**	**Difference**	**T**	**p**	**95% CI**	**Post-training Mean****	**CF vs.**	**p**	**95% CI**	**TRAD vs.**	**p**	**95% CI**
Aerobic Capacity	**20 Meter Shuttle Run Test Score**	**CF**	Pre	7.08 ± 0.74	**0.85 ± 0.22***	**(9) = 3.90**	**.004**	**0.36, 1.34**	7.90 ± 0.23						
			Post	7.93 ± 0.79											
		TRAD	Pre	7.70 ± 0.74	0.42 ± 0.27	(9) = 1.54	.157	-0.20, 1.04	7.45 ± 0.23						
			Post	8.12 ± 0.79											
		FE	Pre	6.37 ± 0.74	0.30 ± 0.17	(9) = 1.81	.103	-0.07, 0.67	7.37 ± 0.23						
			Post	6.67 ± 0.79											
	Estimated VO2max (ml/kg/min)	**CF**	Pre	41.60 ± 2.20	**2.10 ± 0.78***	**(9) = 2.69**	**.025**	**0.33, 3.87**	43.50 ± 0.72						
			Post	43.70 ± 2.33											
		TRAD	Pre	43.70 ± 2.20	0.30 ± 0.70	(9) = 0.43	.678	-1.28, 1.88	41.68 ± 0.74						
			Post	44.00 ± 2.33											
		FE	Pre	38.90 ± 2.20	0.90 ± 0.64	(9) = 1.41	.193	-0.55, 2.35	42.32 ± 0.74						
			Post	39.80 ± 2.33											

**Indicates statistical significance (p<0.05); CF = Crossfit training intervention; TRAD = Traditional training intervention; FE = Free Exercise training intervention; ** = adjusted for between group differences in pre-training means (as the covariate); CI = Confidence Interval.*

Appendix F: Musculoskeletal Strength Data – Within and Between Group Comparisons

				Within Group Comparisons (Pre- vs. Post-training)					Between Group Comparisons (Difference in Post-training Mean**)
Section	**Test**	**Group**	**Time**	**Mean**	**Difference**	**T**	**p**	**95% CI**	**Post-training Mean****
Musculoskeletal Strength	**Barbell Back Squat Estimated 1 Repetition Maximum (lb)**	**CF**	Pre	171.21 ± 25.47	**26.63 ± 9.08***	**(9) = 2.93**	**.017**	**6.10, 47.17**	214.79 ± 9.79
			Post	197.84 ± 30.00					
		TRAD	Pre	193.53 ± 25.47	**26.07 ± 8.87***	**(9) = 2.94**	**.017**	**6.00, 46.13**	211.62 ± 9.74
			Post	219.60 ± 30.00					
		FE	Pre	194.42 ± 24.47	20.73 ± 11.77	(9) = 1.76	.112	-5.90, 47.35	206.18 ± 9.74
			Post	215.14 ± 30.00					
	Barbell Bench Press Estimated 1 Repetition Maximum (lb)	**CF**	Pre	115.76 ± 18.33	**9.67 ± 3.15***	**(9) = 3.07**	**.013**	**2.54, 16.80**	133.92 ± 2.71
			Post	125.43 ± 18.92					
		TRAD	Pre	128.02 ± 18.33	**7.96 ± 3.12***	**(9) = 2.55**	**.031**	**0.89, 15.03**	131.93 ± 2.70
			Post	135.97 ± 18.92					
		FE	Pre	128.41 ± 18.33	**5.96 ± 1.36***	**(9) = 4.39**	**.002**	**2.89, 9.04**	129.93 ± 2.70
			Post	134.37 ± 18.92					
	Leg Extension Estimated 1 Repetition Maximum (lb)	**CF**	Pre	201.33 ± 19.15	**42.82 ± 11.68***	**(9) = 3.67**	**.005**	**16.40, 69.24**	239.36 ± 10.25
			Post	244.15 ± 18.43					
		TRAD	Pre	193.55 ± 19.15	**53.32 ± 12.17***	**(9) = 4.38**	**.002**	**25.78, 80.86**	248.37 ± 10.23
			Post	246.87 ± 18.43					
		FE	Pre	191.33 ± 19.15	**18.59 ± 7.66***	**(9) = 2.43**	**.038**	**1.25, 35.93**	213.20 ± 10.24
			Post	209.91 ± 18.43					

Pull-up Estimated 1 Repetition Maximum (lb)	**CF**	Pre	151.98 ± 15.22	**12.73 ± 3.35***	**(9) = 3.81**	**.004**	**5.16, 20.30**	166.35 ± 3.34
		Post	164.71 ± 15.29					
	TRAD	Pre	161.08 ± 15.22	**14.23 ± 3.89***	**(9) = 3.66**	**.005**	**5.42, 23.03**	168.02 ± 3.36
		Post	175.31 ± 15.29					
	FE	Pre	147.89 ± 15.22	**6.35 ± 2.49***	**(9) = 2.55**	**.031**	**0.71, 11.98**	159.89 ± 3.35
		Post	154.24 ± 15.29					
Leg Curl Estimated 1 Repetition Maximum (lb)	**CF**	Pre	123.43 ± 11.55	**12.75 ± 3.57***	**(9) = 3.57**	**.006**	**4.68, 20.83**	130.44 ± 3.07
		Post	136.19 ± 11.09					
	TRAD	Pre	122.85 ± 11.55	**18.16 ± 3.15***	**(9) = 5.76**	**<.001**	**11.02, 25.29**	135.80 ± 3.07
		Post	141.01 ± 11.09					
	FE	Pre	105.35 ± 11.55	**10.51 ± 2.56***	**(9) = 4.10**	**.003**	**4.72, 16.31**	126.83 ± 3.11
		Post	115.86 ± 11.09					

**Indicates statistical significance (p<0.05); CF = Crossfit training intervention; TRAD = Traditional training intervention; FE = Free Exercise training intervention; ** = adjusted for between group differences in pre-training means (as the covariate); CI = Confidence Interval.*

Appendix G: Musculoskeletal Endurance Data – Within and Between Group Comparisons

			Within Group Comparisons (Pre- vs. Post-training)						Between Group Comparisons (Difference in Post-training Mean**)						
Section	**Test**	**Group**	**Time**	**Mean**	**Difference**	**T**	**p**	**95% CI**	**Post-training Mean****	**CF vs.**	**p**	**95% CI**	**TRAD vs.**	**p**	**95% CI**
Musculoskeletal Endurance	**Maximum Bodyweight Squats in 60 Seconds**	**CF**	Pre	49.40 ± 2.31	**4.20 ± 1.42***	**(9) = 2.96**	**.016**	**0.99, 7.41**	55.21 ± 1.25						
			Post	53.60 ± 2.22											
		TRAD	Pre	54.40 ± 2.31	**2.20 ± 0.70***	**(9) = 3.16**	**.012**	**0.63, 3.77**	54.19 ± 1.27						
			Post	56.60 ± 2.22											
		FE	Pre	50.40 ± 2.31	**4.40 ± 1.58***	**(9) = 2.79**	**.021**	**0.83, 7.97**	55.61 ± 1.24						
			Post	54.80 ± 2.22											
	Bent-arm Hang Time to Failure	**CF**	Pre	22.39 ± 5.56	**3.63 ± 0.89***	**(9) = 4.10**	**.003**	**1.63, 5.64**	27.54 ± 1.37						
			Post	26.02 ± 5.33											
		TRAD	Pre	27.65 ± 5.56	-1.38 ± 1.73	(9) = -0.79	.447	-5.29, 2.54	22.91 ± 1.38	**4.63 ± 1.95***	**.026**	**0.61, 8.64**			
			Post	26.27 ± 5.33											
		FE	Pre	22.05 ± 5.56	**3.45 ± 1.46***	**(9) = 2.36**	**.042**	**0.15, 6.74**	27.33 ± 1.37	0.21 ± 1.94	.913	-3.77, 4.19	**-4.42 ± 1.96***	**.033**	**-8.43, -0.40**
			Post	25.49 ± 5.33											
	Leg Extension Repetitions to Failure (at 50% E1RM)	**CF**	Pre	19.30 ± 1.63	2.90 ± 1.49	(9) = 1.94	.084	-0.48, 6.28	23.33 ± 1.51						
			Post	22.20 ± 1.83											
		TRAD	Pre	24.50 ± 1.63	1.10 ± 1.48	(9) = 0.74	.476	-2.25, 4.45	23.20 ± 1.61	0.14 ± 2.29	.953	-4.59, 4.84			
			Post	25.60 ± 1.83											
		FE	Pre	19.10 ± 1.63	-3.00 ± 1.66	(9) = -1.81	.104	-6.76, 0.76	17.37 ± 1.52	**5.96 ± 2.10***	**.009**	**1.65, 10.28**	**5.83 ± 2.30***	**.018**	**1.09, 10.56**

		Post	16.10 ± 1.83					
Bench Press Repetitions to Failure (at 50% E1RM)	**CF**	Pre	28.00 ± 1.83	1.30 ± 1.75	(9) = 0.74	.477	-2.66, 5.26	28.18 ± 1.44
		Post	29.30 ± 1.60					
	TRAD	Pre	25.60 ± 1.83	2.00 ± 1.30	(9) = 1.54	.158	-0.94, 4.94	27.56 ± 1.39
		Post	27.60 ± 1.60					
	FE	Pre	23.10 ± 1.83	1.50 ± 1.95	(9) = 0.77	.460	-2.90, 5.90	25.73 ± 1.44
		Post	24.60 ± 1.60					
Leg Curl Repetitions to Failure (at 50% E1RM)	**CF**	Pre	26.60 ± 2.45	1.60 ± 2.59	(9) = 0.62	.552	-4.25, 7.45	28.18 ± 1.63
		Post	28.20 ± 2.23					
	TRAD	Pre	29.70 ± 2.45	**4.60 ± 1.23***	**(9) = 3.74**	**.005**	**1.82, 7.38**	32.31 ± 1.68
		Post	34.30 ± 2.23					
	FE	Pre	23.40 ± 2.45	2.00 ± 1.36	(9) = 1.47	.175	-1.07, 5.07	27.41 ± 1.68
		Post	25.40 ± 2.23					

**Indicates statistical significance (p<0.05); with the exception of bent arm hang time (which is displayed in seconds), all other test values are displayed as a number of repetitions; CF = Crossfit training intervention; TRAD = Traditional training intervention; FE = Free Exercise training intervention; ** = adjusted for between group differences in pre-training means (as the covariate); CI = Confidence Interval.*

Appendix H: CrossFit Training Program and Workout Examples

https://docs.google.com/spreadsheets/d/15OEtpUEpDgmcaiwK2aZi-eeffE6-gHlbMZ0YqS3FvVw/edit?usp=sharing

Day 3 - MGW

Warm Up (25-30 min)

Exercise	Set	Target Reps/Time	Intensity/Load	Notes
Run, Row, Ski, or Ride	1	800m	75% sprint	
Wall Squat	1	15		Circuit
TRX Row		15		
Pushups		15		
Sit-ups		15		
KB Deadlifts OR 1 Leg KB Deadlifts		15 (or 8 each side)		
Deep Goblet Squats + Rotations	1	15		Circuit
Pull-ups OR Band Assisted Pull-ups		15		
TRX OH Stability Drill		15		
Ab Mat sit-ups OR Legs up sit-ups		15		
Supermans (3 sec pause at top)		15		
TGU OR 1H OH Lunge	2	8 each side		Circuit
Front squats with 3 sec pause at the bottom		6		
Shoulder press + 3 sec pause OH		6		
Thrusters (FSPP) No weight		12		

Workout (25-30 min)

Exercise	Set	Target Reps/Time	Intensity/Load	Notes
- 1-2 warm-up sets - Increase weight each set (up to listed Intensity/Load) - Do not work to failure on warm-up sets				
Thruster Technique + Pull-up Scaling/specific warmup	1		5-10 mins	- Warm up pull-ups (novice = TRX w. legs bent; intermediate = TRX w. legs straight; advanced = pull-ups from bar with band assist; expert = bodyweight pull-ups from bar)
Row or Ski	See Notes	400m		As many rounds as possible in 20 min
Pull-ups		10	- Novice: TRX w. legs bent - Intermediate: TRX w. legs straight - Advanced: pull-ups from bar with band assist - Expert: bodyweight pull-ups from bar	
Thuruster (FSPP)		15	50% BW	

Appendix I: Traditional Training Program and Workout Examples

https://docs.google.com/spreadsheets/d/1ATPxAP7nGBOnuLeTj4vUJdS9ebptntOVUZXYV9oD3-k/edit?usp=sharing

Day A

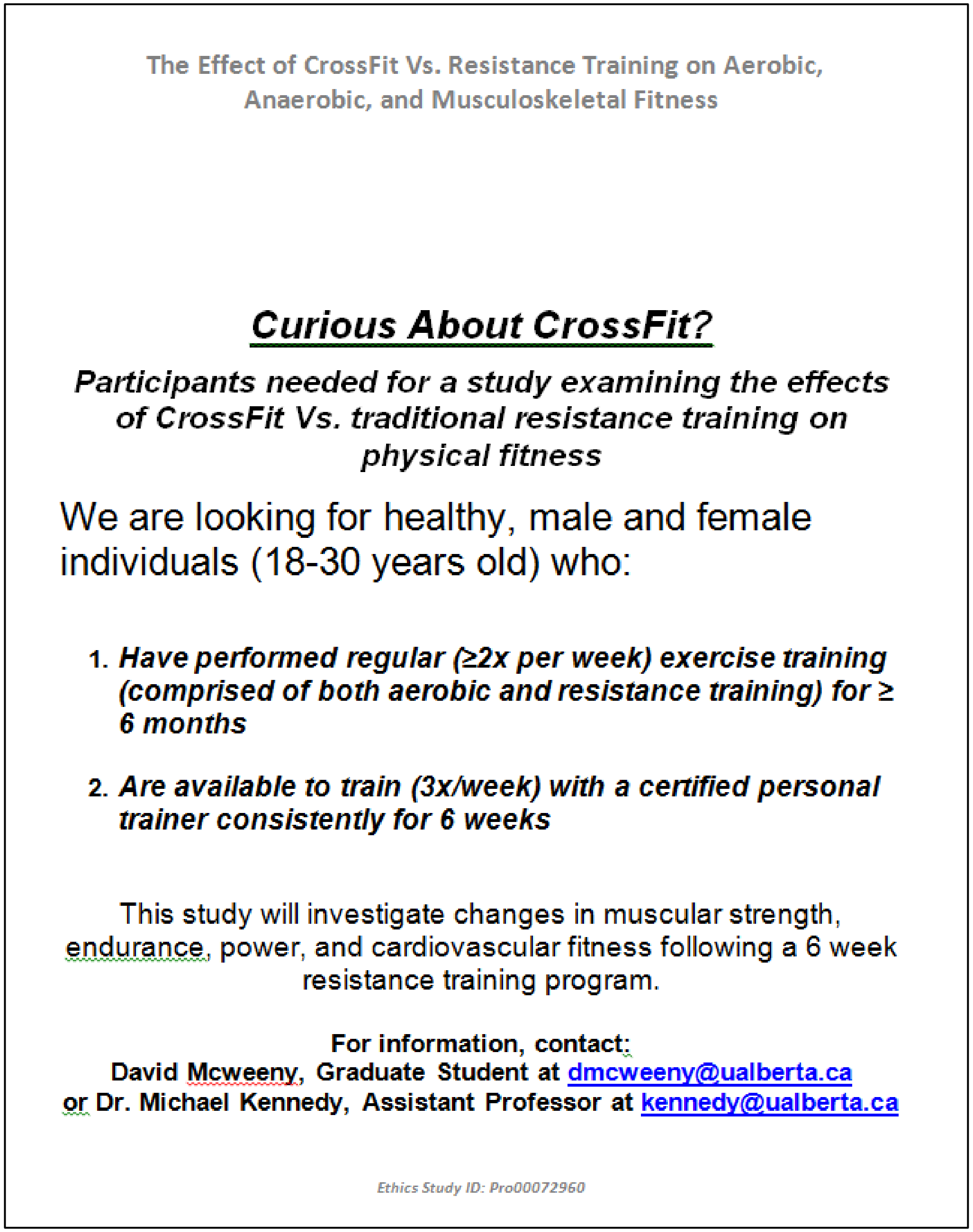
Warm Up

Exercise	Set	Target Reps/Time	Intensity/Load	Notes
Run, Row, Ski, or Ride	1	5-10 minutes	Until light sweat	

Workout

Exercise	Set	Target Reps/Time	Rest	Notes
- 1-3 warm-up sets/exercise - Increase weight each set (up to listed Intensity/Load) - Do not work to failure on warm-up sets				
Flat BB/DB Bench Press	3	12-14	1:30 between sets	- Complete all working sets to failure (i.e. maximal effort apparent at 12-14 reps) - When weight is too heavy (i.e. cannot complete prescribed reps): rest-pause as necessary to complete prescribed reps; scale weight down on subsequent set - When weight is too light (i.e. completes all prescribed reps with ease): scale weight up on subsequent set
Incline DB Chest Fly	3	12-14		
Seated DB/BB Shoulder Press	3	12-14		
Standing DB Lateral Raise	3	12-14		
Seated DB Arm Curl	3	12-14		
Standing BB/Cable Biceps Curl	3	12-14 (OMIT if workout time is at risk of exceeding 70 mins)		
Cable/OH DB Triceps Extension	3	12-14		
Close Grip BB Bench Press	3	12-14 (OMIT if workout time is at risk of exceeding 70 mins)		

Appendix J: Recruitment Poster



The Effect of CrossFit Vs. Resistance Training on Aerobic, Anaerobic, and Musculoskeletal Fitness

Curious About CrossFit?

Participants needed for a study examining the effects of CrossFit Vs. traditional resistance training on physical fitness

We are looking for healthy, male and female individuals (18-30 years old) who:

1. ***Have performed regular (≥2x per week) exercise training (comprised of both aerobic and resistance training) for ≥ 6 months***
2. ***Are available to train (3x/week) with a certified personal trainer consistently for 6 weeks***

This study will investigate changes in muscular strength, endurance, power, and cardiovascular fitness following a 6 week resistance training program.

For information, contact:
David Mcweeny, Graduate Student at dmcweeny@ualberta.ca
or Dr. Michael Kennedy, Assistant Professor at kennedy@ualberta.ca

Ethics Study ID: Pro00072960

Appendix K: Information Email and Informed Consent Form

INFORMATION LETTER and CONSENT FORM

The Effect of CrossFit Vs. Resistance Training on Aerobic, Anaerobic, and Musculoskeletal Fitness

Primary Investigator:
Dr. Michael Kennedy
4-230 Van Vliet Complex
University of Alberta
Edmonton, AB,T6G 2H9
kennedy@ualberta.ca
(780) 492-2830

Co-Investigator:
David Mcweeny
1-320 Van Vliet Complex
University of Alberta
Edmonton, AB, T6G 2H9
dmcweeny@ualberta.ca
(780) 492-7753

Background:

The present study will evaluate the effects of different resistance training methodologies on multiple fitness attributes. You have been invited to voluntarily participate in this study because you perform regular exercise and are between the ages of 18-30. The results from this study will be used to advance academic knowledge in the sports science field, and may be published in related scientific journals, and/or presented at academic conferences in the near future. I (David Mcweeny) will also be using data collected from you (during the study) to complete my Master's thesis in Kinesiology.

Purpose:

Crossfit (CF) is a modality of RT that combines cardiovascular and whole-body musculoskeletal exercises in "workouts of the day" (WOD)), and reflects the variety, intensity and physiological demands that are required to improve multiple fitness components. Interestingly, CF (although a very popular for-profit business model) has limited scientific evidence associated with health and sport performance outcomes, and has a controversial role as a viable alternative to traditional RT programs. Thus the purpose of this project is to examine the effectiveness of CF compared to a traditional RT program on fitness variables. The findings from this study will provide novel insight into the efficacy of CF as a means of improving aerobic, anaerobic, and musculoskeletal fitness attributes relative to more traditional RT modalities in recreationally fit adults.

Study Procedures:

This study will last 8 weeks in duration. If you are eligible for the study, you will be contacted by the research investigator at least 1 week prior to the first scheduled testing session. An initial one-on-one pre-screening meeting will follow, during which you will be asked a series of questions (indicating your frequency and duration of habitual exercise), a physical activity readiness questionnaire (PAR-Q+) (consisting of questions regarding your overall health), and a resting heart rate and blood pressure measure (administered by a certified personal trainer on the research team). If the PAR-Q+ and resting measurements identify pre-existing health conditions that may be aggravated by exercise training/testing within the current study, you will be referred to a physician, and asked to complete a follow-up form PAR-MEDX.

Training:

Once granted entrance into the study, you will be randomly assigned to one of 3 groups - your responses to preliminary questions and PAR-Q+ will have no impact on the group you are assigned to.

If you are assigned to the first (traditional resistance training - TRAD) group, you will be asked to complete a resistance training session (lasting 60-90 minutes) 3x/ week, for 6 weeks in duration. All training sessions will occur in partners (determined based on participant availability), and take place in the Hanson Fitness and Lifestyle Center (HFLC) located at the University of Alberta – we will request that you log attendance and brief details (e.g. time to complete the training session, number of exercises completed) of each workouts in individual training journals, available at the front desk of the HFLC. These journals will be kept confidential, in a locked cabinet – only HFLC staff will be able to access the cabinet, and instructed prior to study initiation only to open the cabinet when a study participant requests their journal. When you request access to your journal, a front desk attendant will ask you for your name and email address – if these match what is written on the front of your journal, the staff member will give you your journal. The exercises, repetitions, sets and other workout variables will be prescribed by a Canadian Society for Exercise Physiology (CSEP) certified personal trainer. Most training sessions will be actively supervised by a certified personal trainer – this individual will guide you through proper exercise form, and address any questions you have regarding the 6 week training program. These training sessions will also include demonstrations on how to determine the amount of weight you should be lifting during each exercise. In the event that a personal trainer is unavailable during part or all of a training session, there will be qualified professionals available at the HFLC who will be able to demonstrate correct exercise form during all training sessions. Although we will attempt to find a personal trainer that can accommodate your weekly availability for training, you may be asked to perform unsupervised workouts during times/days that fit best within your schedule (as long as a minimum of 24 hours have elapsed between the two resistance training sessions you complete each week, and all of your training sessions occur within the HFLC). If you have future plans that may result in you missing 4 or more workouts during the 6 week study period (including travel plans that would prevent you from training in the HFLC for at least 2 consecutive weeks), we would ask that you inform the research team during the pre-screening period.

If you are assigned to the second training (CrossFit - CF) group, you will also be asked to complete 6 weeks of CF style resistance training (3x/week, lasting 60-90 minutes each session) at the HFLC – all workouts you perform will occur in partners and be led/supervised by a CSEP certified personal trainer. Training variables (e.g. exercises, repetitions, sets) will be determined by a CSEP certified personal trainer, and shared with participants upon arrival for each workout session. The amount of weight you will be lifting during each exercise will be determined by the personal trainer responsible for leading the workout. This individual will also demonstrate and actively monitor exercise technique during all training sessions. Training sessions will occur at the same times and days, every week – if you have future plans that may interfere with your ability to attend at least 14 of the 18 scheduled training sessions, we would ask that you inform members of the research team during the pre-screening period. A schedule outlining specific times/days of training sessions will be shared with you once assigned to group 2. We also request that you log training session attendance and brief workout details in individual training journals (located at the front desk of the HFLC). Journals for all groups will be kept in the same locked cabinet at the front desk of the HFLC – you must provide your name and email address to the front desk attendant in order to access your training journal.

Although other forms of unloaded exercise (e.g. running, cycling swimming) will be permitted during the study, we ask that participants in both the TRAD and CF groups **do not** perform any other resistance training outside of the workouts prescribed to you by the research team. We will request that you log all forms of structured physical activity (including unloaded exercise) completed during the study duration in your personal training journal.

If you are assigned to the third group (Free Exercise – FE), you will continue to perform your regular exercise program during 6 week period. Similar to individuals assigned to the first two groups, we will request that you log all details pertaining to structured exercise in your individual training journal, (located in the locked cabinet at the HFLC front desk.

Assessment:

Regardless of what group you are assigned to, you will be asked to perform 6 days of fitness testing during the 8 week study period. The purpose of these tests is to assess the impacts of each 6 week program on aerobic, anaerobic, and musculoskeletal fitness variables. The first round of testing will occur prior to the first week of training (within 7 days of your first scheduled workout); the second round of testing will take place after the last week of training (within 7 days of your last scheduled workout) - if you are assigned to the FE group, you will perform the same tests during the same pre- and post-training periods as individuals in the TRAD and CF (despite not being scheduled for any resistance training sessions).

During each round of testing, you will be asked to complete 3 days of tests (lasting approximately 1-1.5 hours each day) – these tests will be scheduled on consecutive days (separated by no more than 24 hours) during which we request that you do not engage in any other forms of exercise,. All testing will occur in the Van Vliet Center at the University of Alberta. A schedule of each testing day can be seen in the below figure – all testing days will be repeated during the pre- and post-training periods.

	Testing Day		
	1	**2**	**3**
Assessment Name	Upper body Wingate	VO2 max	Vertical jump
	Maximal squat repetitions to medicine ball in 1 minute	1-RM back squat	Lower body Wingate
	Bent arm dead hang to failure	1-RM pull up/assisted pull up	Medicine ball put
	1RM familiarization (back squat, pull-up, leg extension, bench press, leg curl)	1-RM leg extension	50% 1-RM leg extension
	CF Technique clinic (CF ONLY) (front squat, overhead squat, push press, deadlift, sumo deadlift high pull, medicine ball clean)	1-RM bench press	50%1-RM bench press
		1-RM leg curl	50% 1-RM leg curl

Participants in all groups will undergo 3 days of testing during the 1st and 8th week of the study intervention – no longer than 48 hours will be permitted between the first and second testing days; both testing days will occur within 7 days of the training intervention initiation, and then be repeated at the end of the study (within 7 days of the last training session). 3-5 minutes rest will be permitted between each assessment.

Upon arrival for all testing days, you will complete a preliminary assessment (consisting of signing a PAR-Q+ and undergoing resting heart rate and blood pressure measures). Once cleared for testing by a CSEP certified personal trainer, you will spend 5-10 minutes warming up on a stationary bicycle and performing dynamic stretches. You will then perform tests in the above table in chronological order – 3-5 minutes of rest will follow each test.

Most of these tests are non-invasive, and involve assessments of either maximal power (i.e. how high you can jump or how far you can throw a medicine ball), endurance (i.e. the maximum amount of time you can hang from a pull-up bar before touching the ground), or strength (i.e. the maximum amount of weight you can squat or pull-down within 3 repetitions). If the preliminary assessment identifies any pre-existing medical conditions or medical conditions that may be aggravated by testing, you will not perform these tests.

There are also tests that will involve maximal effort performances (i.e. lower and upper body Wingate, and treadmill VO2max) – these tests involve all-out sprinting on an arm or leg powered stationary bike (for 30 seconds), and running on a treadmill that increases in speed and inclination until exhaustion (respectfully). The maximal effort nature of these tests may cause you some immediate discomfort – if you feel unable to tolerate this discomfort at any time, you may voluntarily stop the test. Additionally, precautions will be taken by the members of the research team to limit these feelings during testing.

The treadmill VO2max test requires that you breath into a portable metabolic device (which will monitor how much oxygen you are consuming during exercise) for several minutes – because your nose will be plugged during these maximal effort tests, continuous breathing into and out of a tube (connected to the metabolic device) may result in feelings of dry mouth, and associated discomfort. However, this test will last only a few minutes in duration, you will be free to stop the tests at any time if this discomfort becomes intolerable, and you will be permitted to re-hydrate immediately prior to and following testing.

Blood lactate will be measured during the VO2max and lower/upper body Wingate. 5 minutes prior to test initiation, as well as 3 and 7 minutes post testing, a member of the research team will prick your finger tip with a small pin – this will break your skin, such that a small amount of blood can be placed on a strip of paper and subsequently analyzed for blood lactate concentration by an automated device. Although breaking your skin may cause a small amount of immediate pain (you will feel a small pinch when we prick your finger), this process takes less than one second, and is minimally invasive – only a small portion of your skin must be broken in order to measure blood lactate pre and post exercise. All blood lactate measures will be performed by a member of the research team with previous training, certification, and experience in performing blood collection procedures. If you are uncomfortable with having blood taken, you will not be required to undergo blood lactate testing.

Benefits:

There is no costs associated with volunteering to participate in the current study. Additionally, if you agree to participate in the current study, you will benefit by receiving a 6 week resistance training program, exercise instruction by a certified exercise professional, and gold standard fitness test results. If you are assigned to group 1 (TRAD), you will have access to the training program utilized by group 2 (CF) (and vice versa) following the 6 week intervention. If you are assigned to group 3 (FE), you will have access to both programs, upon completion of the 6 week intervention. Although we require that you possess adequate initial fitness prior to starting the training interventions, it is likely that you will achieve positive physiological adaptations to training (such as improvements in muscular strength, endurance, and/or cardiovascular fitness) by following either of the training programs prescribed during this study.

The benefits of participating in this study outweigh the potential risks. Regular resistance training offers well known health benefits (and associated physiological outcomes).

Risk:

Although the risk of serious health conditions resulting from the aforementioned testing and training protocols is low, there is always inherent risk when performing any maximal effort training and/or testing. Participation in the current study means that you assume the risks associated with very hard exercise (e.g. muscle pulls, strains, cramps, abnormal blood pressure, fainting, nausea, and, in very rare cases, heart disturbances, possibly leading to heart attack).

Further risks of injury and health issues incurred through training will be heavily mitigated by professional supervision, as well as instruction by individuals who have obtained certification from accredited fitness and organizations. Additionally, you will be pre-screened before initiation of training and testing for health conditions that may predispose you to an increased chance of injury during training/testing – if you have adverse health conditions and/or injuries, we will ask that you consult a physician for exercise clearance, prior to participating in any training/testing. During all situations in which the supervising certified exercise professional interprets the risk of participating in resistance training or exercise testing as greater than the potential benefits of participation, the protocol will not be initiated, and you may be rejected from the study (in the interest of maintaining your health and wellbeing).

Voluntary Participation:

You will be free to withdraw at any point of the study, without any penalty or repercussion. The freedom to withdraw is explicitly stated on the informed consent form.

You will also free to refrain from attempting any exercise(s) prescribed during the training intervention. Certified personal trainers on the research team will attempt to modify/regress exercises that are too difficult and/or not possible for you to perform - this process will be completed on an individual basis, depending on your specific exercise limitations. You may also refrain from any exercise tests (including measures requiring maximal aerobic tests, maximal anaerobic tests, and/or musculoskeletal tests) included within the study protocol, at any time.

If you miss more than 4 training sessions and/or become unavailable to be contacted, it will be assumed that you have withdrawn yourself from the study. If you withdraw yourself from the study, and request data removal at withdrawal, all records of your test results and personal information will be eliminated immediately. If you withdraw from the study, but do not request removal of the data we collected about you, this data will be used to perform study analysis, then eliminated when all other participant data is deleted.

Confidentiality & Anonymity:

Data collected from you during the current study will be used to complete a Master's Thesis and may be used in subsequent presentations to university students and at academic conferences. Depending on the outcome of this study, these results may also be published in suitable academic journals. However, no individuals outside of the research team will be able to connect any data we collected from you during the study, to your identity. Upon successful recruitment into the study, a study ID number will be randomly assigned to your identity. Data we collect from you will then be stored in a computer file under your assigned study ID. A master list will be created to link participant identifiers with their file name; access to these files will be limited to members of the research team. All members of the research team will be briefed (prior to study initiation) regarding the responsibilities concerning privacy and confidentiality of participants. Members of the research team will also be selected based on their perceived maturity and ability to maintain this confidentiality.

All of your data and associated records will be stored in a locked file cabinet in VVC 1-320 (Hanson Fitness and Lifestyle Center), which is an office with key access. The primary investigator has a work station in this office. The electronic records and data associated with your identity will be stored on a password encrypted excel document - the password to this document will only be shared with necessary members of the research team.

Any physical paper files will be kept in a locked file cabinet in the supervisor's laboratory, following completion of the study. Any digital records will be kept in a password encoded excel document until analysis and dissemination of results has occurred. Following these processes, all digital files associated with the current study will be transferred to a secure hard drive on a password protected desktop computer in the supervisor's laboratory.

Further Information:

If you have any further questions regarding this study, please do not hesitate to contact David Mcweeny or Michael Kennedy. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

Consent Statement:

I have read this form and the research study has been explained to me. I have been given the opportunity to ask questions and my questions have been answered. If I have additional questions, I have been told whom to contact. I agree to participate in the research study described above and will receive a copy of this consent form. I will receive a copy of this consent form after I sign it.

CONSENT

Title of Study: The Effect of CrossFit Vs. Resistance Training on Aerobic, Anaerobic, and Musculoskeletal Fitness

Principal Investigator: Dr. Michael Kennedy, ph 780 492 2830

Co-Investigator: David Mcweeny, ph 780 492 7753

	Yes	No
Do you understand that you have been asked to be in a research study?	☐	☐
Have you read and received a copy of the attached Information Sheet?	☐	☐
Do you understand the benefits and risks involved in taking part in this research study?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Do you understand that you are free to leave the study at any time, without having to give a reason and without affecting your future medical care?	☐	☐
Has the issue of confidentiality been explained to you?	☐	☐
Do you understand who will have access to your records, including personally identifiable health information?	☐	☐

Do you want the investigator(s) to inform your family doctor that you are ☐ ☐

participating in this research study? If so, give his/her name __________________

Who explained this study to you? ____

I agree to take part in this study:

Signature of Research Participant ____

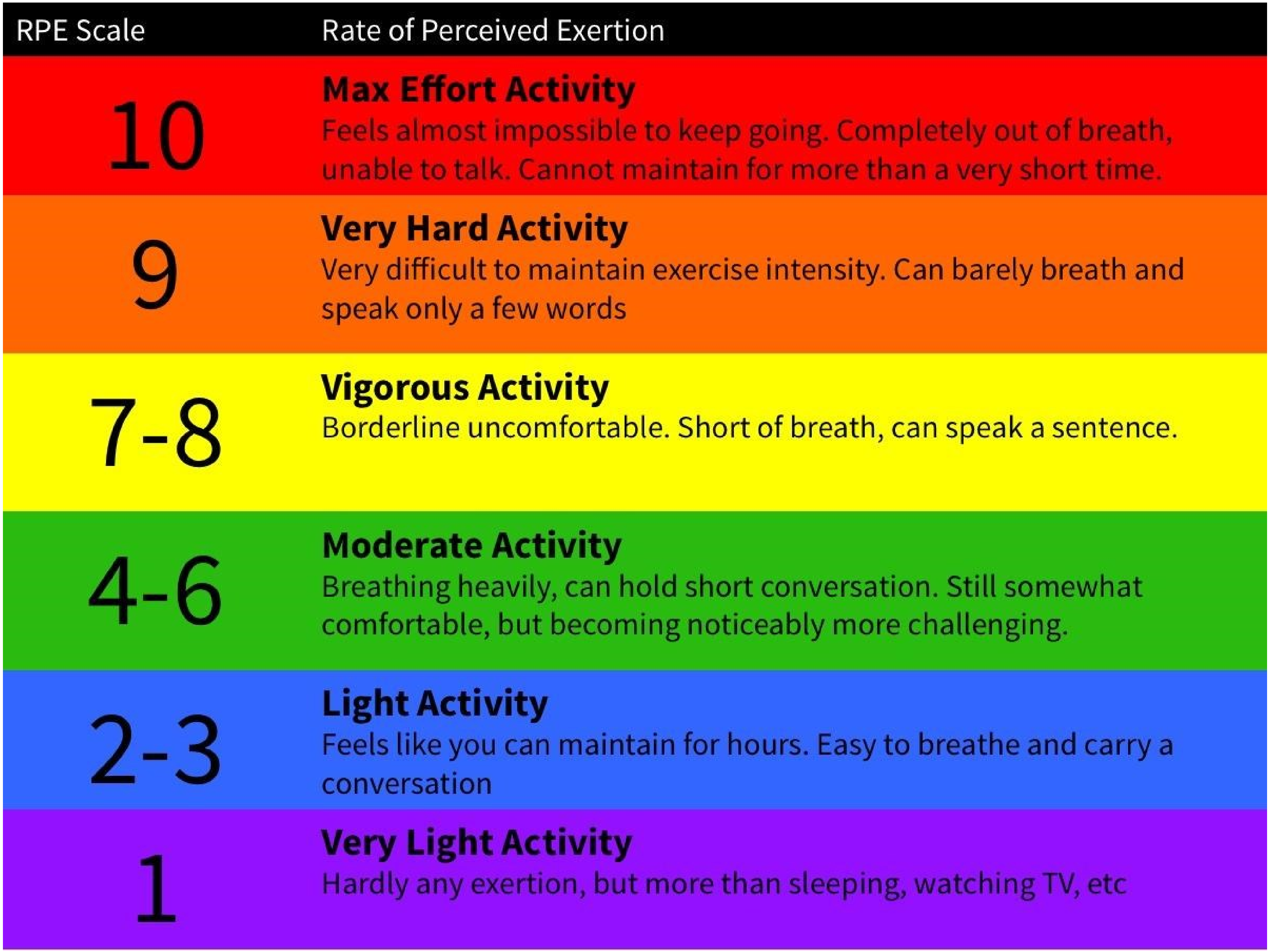
(Printed Name)____

Date:______________________________

Signature of Investigator or Designee_______________________Date _____________.______

THE INFORMATION SHEET MUST BE ATTACHED TO THIS CONSENT FORM AND A SIGNED COPY GIVEN TO THE RESEARCH PARTICIPANT

Appendix L: Participant Training Log



RPE Scale	Rate of Perceived Exertion
10	**Max Effort Activity** Feels almost impossible to keep going. Completely out of breath, unable to talk. Cannot maintain for more than a very short time.
9	**Very Hard Activity** Very difficult to maintain exercise intensity. Can barely breath and speak only a few words
7-8	**Vigorous Activity** Borderline uncomfortable. Short of breath, can speak a sentence.
4-6	**Moderate Activity** Breathing heavily, can hold short conversation. Still somewhat comfortable, but becoming noticeably more challenging.
2-3	**Light Activity** Feels like you can maintain for hours. Easy to breathe and carry a conversation
1	**Very Light Activity** Hardly any exertion, but more than sleeping, watching TV, etc

PARTICIPANT NUMBER_________________

Week #	Date (dd/mm/yy)	Day	Activity	Description	Duration	RPE (see above picture)
1		**Monday**	E.g. Upper Body Workout 1	12-15 rep range	60 min	5
		Tuesday				
		Wednesday				
		Thursday				
		Friday				
		Saturday				
		Sunday				

Appendix M: Testing and Training Timelines and Schedules

		Week							
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Group	**FE**	**Test Day 1**	**Maintain Habitual Exercise**						**Test Day 1**
		Test Day 2							**Test Day 2**
		Test Day 3							**Test Day 3**
	CF	**Test Day 1**	**CF Workouts (14-18 workouts)**						**Test Day 1**
		Test Day 2							**Test Day 2**
		Test Day 3							**Test Day 3**
	TRAD	**Test Day 1**	**TRAD Workouts (14-18 workouts)**						**Test Day 1**
		Test Day 2							**Test Day 2**
		Test Day 3							**Test Day 3**

Figure 4: *Testing and Training Timeline. Participants were assigned to one of 3 groups prior to study initiation: maintenance of pre-study RT (FE), traditional RT (TRAD), or crossfit RT (CF). During weeks 0 and 7 of the intervention, all groups underwent three days of testing – training was not performed during these weeks. Individuals in the TRAD group were supervised during all RT sessions by a personal trainer up to 4 days per week (during weeks 1-6). Participants in the CF group were guided through Crossfit sessions by a personal trainer up to 4 days per week (during weeks 1-6). The FE group was asked to maintain their habitual training routine during weeks 1-6.*

	Testing Day		
	1	**2**	**3**
Assessment Name	Upper body Wingate	VO2 max	Vertical jump
	Maximal squat repetitions to medicine ball in 1 minute	1-RM back squat	Lower body Wingate
	Bent arm dead hang to failure	1-RM pull up/assisted pull up	Medicine ball put
		1-RM leg extension	50% 1-RM leg extension
		1-RM bench press	50% 1-RM bench press
		1-RM leg curl	50% 1-RM leg curl

Figure 5: *Order of Assessments during Test Days. Participants in all groups (FE, TRAD, and CF) underwent 6 days of testing during the weeks 0 and 7 of study intervention – no longer than 48 hours was permitted between any testing days, and training sessions did not occur during testing weeks. All testing days occurred within 7 days of the training intervention initiation, and were repeated at the end of the study (i.e. within 7 days of the last training session). 3-5 minutes of rest was permitted between each assessment.*